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Deep-Sea Research,, 1955, Vol. 2, pp. 161 to 171. Pergamon Press Ltd., London.

Some bathymetric and geotectonic features of the eastern part of the Indian Ocean[†]

RHODES W. FAIRBRIDGE

Summary—Tectonic relations of the mainland of Western Australia are reflected seawards by the topography of both continental shelf and adjacent deep ocean floor respectively. The basic pattern of the mainland is controlled by the early Pre-Cambrian " grain " (fracture and folding trends). The continental shelf is narrow and rocky where these ancient orogenic lines cross it, and they appear to continue oceanwards in elevations of the deep-sea floor. On the other hand, the Palaeozoic-Mesozoic-Tertiary basins (paraliageosynclines) of the mainland (up to 20,000 feet deep) are matched on the shelf by wide sandy, and atoll-rimmed embayments; and seawards again by oceanic basins approaching 3,000 fathoms in depth. Crustal character of the main eastern Indian Ocean suggests a thalasso-craton (here defined as primary oceanic crust), but these marginal intermediate ridges and basins suggests a common evolution with the continent. Formal names have been given to sectors of the West Australian shelf and the deep-sea floor in the eastern part of the Indian Ocean.

INTRODUCTION

A RECENT study of the Western Australian continental shelf and its sediments by the writer and one of his students (CARRIGY and FAIRBRIDGE 1954) required some consideration of the deep-sea floor in the adjacent parts of the Indian Ocean. No original bathymetric surveys were carried out, but the chart data at present available led to some thought on the geotectonics of the ocean floor and margin; further it was found desirable to apply names to certain bathymetric features which warrant particular nomenclature. Rules laid down by the International Committee on the Nomenclature of Ocean Bottom Features (WISEMAN and OVEY 1953; OVEY 1954) have been adhered to.

The present paper will serve to bring forward some comments on the suspected tectonic significance of the topographic structures delineated, and further, to make available those names in an international journal.

The best available chart of the area concerned is that prepared by VENING MEINESZ (1948) for his latest work on gravity measurements at sea, and here he proposed names for the more outstanding features. The latest edition of the *Carte Générale Bathymétrique des Océans* (sheet A'III) was issued in 1942. A general outline of existing knowledge on the area may be found in SCHOTT (1935).

MAIN TOPOGRAPHIC FEATURES

In another paper (FAIRBRIDGE 1948) it was indicated that the Indian Ocean appears to be divided by the Mid-Indian Ridge into two diverse regions, a western characterized by numerous linear ridges and small basins, and an eastern part marked by a very broad, rather featureless depression (see Fig. 1).

This eastern depression is known as the INDIA-AUSTRALIAN BASIN* (SCHOTT 1935) and occupies approximately 4,000,000 square miles. It is divided in two by an

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† See note at foot of page 171.

* Or " Cocos-Keeling Basin," by the British Committee on the Nomenclature of Ocean Bottom Features (Royal Society, Mimeo., 1951).

ENE-WSW series of scattered submarine plateaux, seamounts and atolls (including Cocos-Keeling and Christmas Island) that correspond to a line joining Java and Madasgascar; lying along the western part of the line, that is west of the Mid-Indian Ridge, are the important volcanic islands of Rodriguez, Mauritius and Reunion.

Echo-sounding traces (see, for example, those published by VENING MEINESZ 1948) of the India-Australian Basin show a relatively flat, featureless floor, in marked contrast to the rugged topography west of the Mid-Indian Ridge. An idea favoured by PETTERSSON (1949), KOCZY (1954), and by GASKELL and ASHTON (1954) is that extensive lava flows might explain the flatness, and also the hardness of the bottom. WEYNSCHENCK (1951) suggests that this is a normal deep sea carbonate sediment that has become dolomitized.

It appears unlikely (to the writer) that this horizontality may be explained purely by sedimentation, as ERICSON, EWING and HEEZEN (1952) would for the floor of the western North Atlantic, because the region is far removed, and topographically isolated, from regions of high sedimentation. The evidence deduced by DIETZ (1953) of sediment filling and turbidity currents in the Bay of Bengal, fed by the great rivers of India, is doubted by KOCZY (1954) and in any case cannot be matched by any such profiles or rivers from the arid continental shores of Western Australia. One might expect to find, as in the Atlantic, numerous little sea-knolls in the marginal areas, such as might represent peaks of a rough topography almost " drowned " by sediment. But this is apparently not the case, except in special areas. A guyot-like knoll is found at 400 fathoms just off the edge of the Rottnest Shelf but this feature is on a different scale altogether; it may represent the stump of a Tertiary basalt eruption, as it lies along the trend of several other small plugs in the coastal plain of southwestern Australia. Numerous knolls and seamounts were found by the Swedish Deep-Sea Expedition (*Albatross*, see KOCZY 1954) and two more sea-mounts were found here by the *Challenger* (GASKELL and ASHTON 1954) in the region south of the Java Trench (the " Christmas Rise " here proposed), but again this is a special area, coming under the influence of the tectonism of the Indonesian mobile belt.

NEW FEATURES DESIGNATED

The new subdivisions of the India-Australian Basin have been recognized within a belt 400 to 500 miles off the Australian side of the basin. There now appear to be a number of marginal ridges and basins here. The principal elevations have been designated as follows :

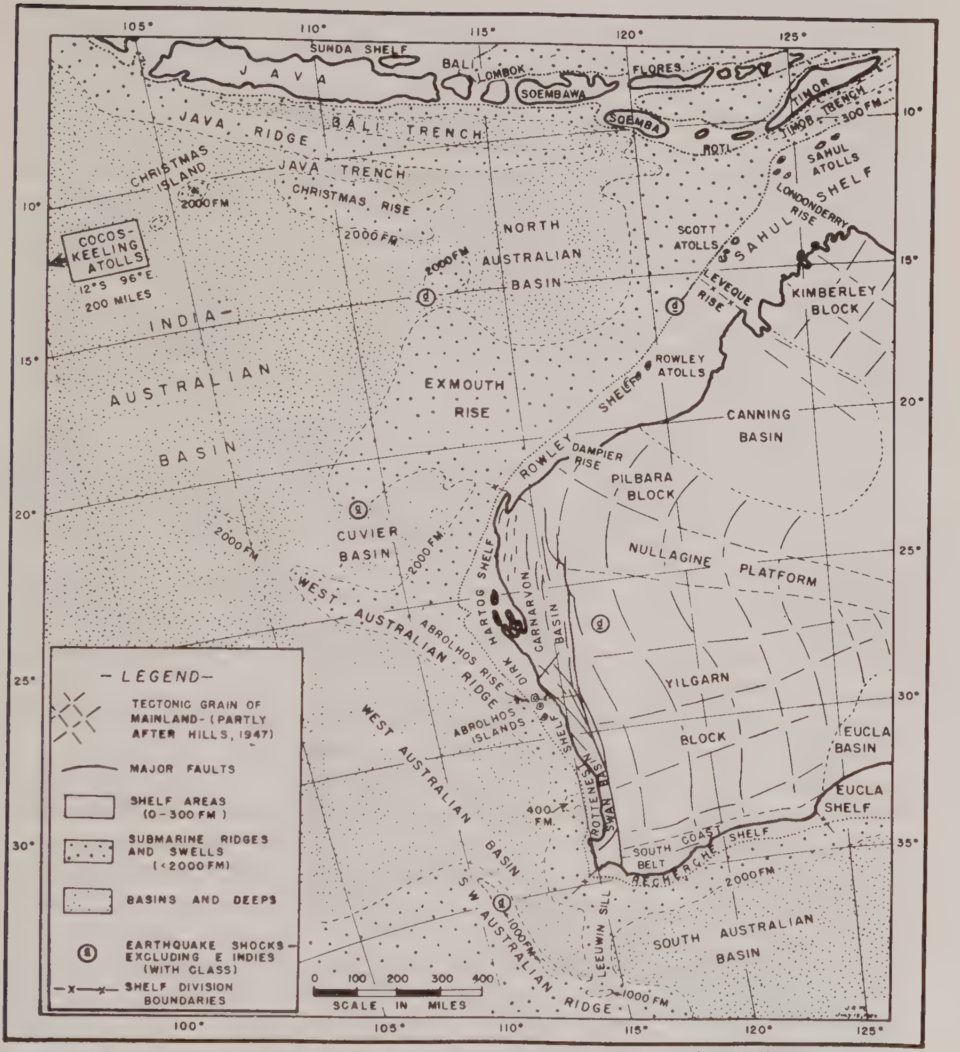
(a) *Leeuwin Sill* (of CARRIGY and FAIRBRIDGE 1954) a low ridge of under 2,000 fathoms depth, connecting the south-western point of Australia, Cape Leeuwin, with the South-West Australian Ridge (of VENING MEINESZ 1948). It trends roughly north and south, and is about 200 miles long. It is termed a " sill " because it forms a partial barrier between the South Australian and West Australian basins.

(b) *West Australian Ridge* (of VENING MEINESZ 1948) is a spur extending north-west from the West Australian mainland from about 30°S in the direction of (but not reaching) the Cocos-Keeling Islands. It is approximately 800 miles long and is almost everywhere less than 2,000 fathoms in depth, along the crest being locally under 1,000 fathoms.

(c) *Exmouth Rise* (of CARRIGY and FAIRBRIDGE 1954) is a broad swell (in tectonic terminology) lying to the north of Exmouth Gulf and north-west of the Pilbara

(2)

district of Western Australia. Its axis appears to be NE-SW, that is, parallel to the coast here, measuring 500 miles by 200 miles. It is only partially surrounded by the 2,000 fathom contour being connected to the mainland by a low and broad platform.


105°
110°
115°
120°
125°
100°
10°
15°
20°
25°
30°
35°
SUNDA SHELF
JAVA
BALI
LOMBOK
SOEMBAWA
FLORES
SOEMBA
ROTI
TIMOR
TIMOR TRENCH
300 FM
SAHUL ATOLLS
JAVA RIDGE
BALI TRENCH
JAVA TRENCH
CHRISTMAS ISLAND
2000 FM
CHRISTMAS RISE
LONDONDERRY RISE
SAHUL SHELF
COCOS-KEELING ATOLLS
12° S 96° E
200 MILES
NORTH AUSTRALIAN BASIN
SCOTT ATOLLS
LEVEQUE RISE
KIMBERLEY BLOCK
INDIA-AUSTRALIAN BASIN
EXMOUTH RISE
ROWLEY ATOLLS
ROWLEY SHELF
CANNING BASIN
DAMPIER RISE
PILBARA BLOCK
CUVIER BASIN
NULLAGINE PLATFORM
WEST AUSTRALIAN RIDGE
ABROLHOS RISE
HARTOG SHELF
CARNARVON BASIN
DIRK
ABROLHOS ISLANDS
YILGARN BLOCK
EUCLA BASIN
EUCLA SHELF
WEST AUSTRALIAN BASIN
SHELF
ROTTENEST
SWAN BASIN
400 FM.
SOUTH BELT
COAST SHELF
RECHERCHE
2000 FM
S W AUSTRALIAN RIDGE
1000 FM
LEEUWIN SILL
SOUTH AUSTRALIAN BASIN
1000 FM
- LEGEND -
TECTONIC GRAIN OF MAINLAND - (PARTLY AFTER HILLS, 1947)
MAJOR FAULTS
SHELF AREAS (0 - 300 FM)
SUBMARINE RIDGES AND SWELLS (<2000 FM)
BASINS AND DEEPS
EARTHQUAKE SHOCKS - EXCLUDING E INDIES (WITH CLASS)
SHELF DIVISION BOUNDARIES
0 100 200 300 400
SCALE IN MILES

R W FAIRBRIDGE

Fig. 1. Bathymetric sketch-map of the eastern part of the Indian Ocean, showing relationships to the tectonic " grain " of Western Australia. Note how the Pre-Cambrian structures of the continent appear to cross the continental shelf and extend into the adjacent deep-sea area; and how the younger basins of the mainland with their broader shelves are reflected off-shore by deep-sea basins.

(d) *Christmas Rise* (now proposed) is a somewhat similar swell almost connected to the Exmouth Rise, but lying to the north and parallel to the Java Trench. It forms, so to speak, an under-developed third arc in the East Indian sequence, but

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clearly lacks the mobility and seismicity of the two main arcs (Inner and Outer Banda Arcs). It extends eastwards from near Christmas Island for 300 miles, and may possibly reach as far as 120°E in depths approaching 3,000 fathoms. The occurrence of such recessive " third arcs " is becoming an accepted feature of most contemporary mobile belts.

In contrast to all these elevations which are characterized by linear developments, there remain between them a number of depressions which are sufficiently distinctive to warrant local designation, yet are each more or less connected with the main India-Australian Basin. Whether or not definite western boundaries may ultimately be found must await more detailed surveys. These depressions are :—

(a) *West Australian Basin* (of VENING MEINESZ 1948) lies south of the West Australian Ridge, north of the South-West Australian Ridge and is separated by the Leeuwin Sill from the South Australian Basin, a fact that has become apparent only since the publication of VENING MEINESZ's map of 1948. The basin is mostly over 3,000 fathoms deep.

(b) *Cuvier Basin* (of CARRIGY and FAIRBRIDGE 1954), named after Cape Cuvier, 200 miles south of North West Cape, lies between the West Australian Ridge and the Exmouth Rise. It is almost enclosed by the 2,000 fathom contour and approaches 3,000 fathoms in depth.

(c) *North Australian Basin* (of CARRIGY and FAIRBRIDGE 1954) lies in the V-shaped angle between the East Indies and north-western Australia. It is bounded on the south-west by the Exmouth Rise, on the north-west by a number of slight elevations leading to the Christmas Rise and the southern margin of the Java Trough. On the east it is limited by the Sahul Shelf.

In our sediment studies of the adjacent continental shelves, it has been found convenient to name these too.* From north to south, they are:

(i) *Arafura Shelf* (KRÜMMEL 1897), from Cape van Diemen (Northern Territory) to New Guinea.
(ii) *Sahul Shelf* (of MOLENGRAAFF and WEBER 1919; restricted by FAIRBRIDGE 1953), from Cape Leveque to Cape van Diemen.
(iii) *Rowley Shelf* (FAIRBRIDGE 1953), from Cape Leveque to North West Cape.
(iv) *Dirk Hartog Shelf* (CARRIGY and FAIRBRIDGE 1954), from North West Cape to Abrolhos Islands (29°S).
(v) *Rottnest Shelf* (CLARKE 1926) from Abrolhos Islands to Cape Leeuwin.
(vi) *Recherche Shelf* (CARRIGY and FAIRBRIDGE 1954), from Cape Leeuwin to Israelite Bay (124°E).
(vii) *Eucla Shelf* (CARRIGY and FAIRBRIDGE 1954), from Israelite Bay to Fowlers Bay, South Australia (132·5°E).

Beyond this point, and still within the bounds of the Indian Ocean (following SCHOTT's limits, 1935), there are several further divisions of the southern Australian shelf, but these have not yet been named.

Most of these shelves are regions of low or interrupted sedimentation (CARRIGY and FAIRBRIDGE 1954), and this may be partially responsible for the lack of submarine canyons reported off Western Australia. A single such canyon was suspected by SHEPARD (1948) off Shark Bay and may correspond to the Pleistocene course of the Gascoyne River; soundings are very sparse, however, and confirmation is needed.

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* An effort has been made to adhere to modern nomenclatorial practice, which requires that whenever possible a geographic name shall be employed in designating bathymetric features. Thus, the Rowley-Sahul Shelves were formerly named " North-west Shelf " (KRÜMMEL 1897); and the writer himself sinned in naming the Rottnest Shelf " West Coast Shelf " (FAIRBRIDGE 1950).

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TECTONIC RELATIONS WITH MAINLAND AND SHELF

Geological studies of the adjacent Australian mainland show that it consists essentially of an ancient, Pre-Cambrian shield of approximately 2,000,000 square miles area, which is marginally overlapped by a series of younger basins (" paralia-geosynclines " in the terminology of MARSHALL KAY 1951; " paralic basins " of TERCIER, see discussion in TEICHERT 1947; named in GENTILLI and FAIRBRIDGE 1951). These represent broad downwarps of the continent, being now filled with up to 20,000 feet of sediments ranging in age from the Palaeozoic to the Quaternary. Locally these sediments are heavily faulted and gently folded (Germanotype tectonics), but nowhere are they affected by major orogenic compression. The amount of downwarp is of the order of 1 to 4 miles distributed over basins 100 to 400 miles wide. It is apparent therefore that the West Australian Shield is a crustal feature of very great longevity and high stability. Large parts of it have hardly been more than gently warped over a period of over 1,000 million years.

Study of the continental shelves marginal to this continent (FAIRBRIDGE 1953; CARRIGY and FAIRBRIDGE 1954) have disclosed the fact the shelves are broadest and deepest opposite the basins on the mainland, while dominant ridges, platforms or positive blocks in the Pre-Cambrian framework are reflected on the continental shelf by a narrow, shallow character. A geomorphologic reflection of these relations may be seen in the fact that the shelves opposite the mainland ridges, are marked by rocky shores and offshore islands of Pre-Cambrian rocks, while the shelves next to the younger basins are marked by sandy shores, with coral reefs and even atolls near the outer parts of the shelf.

The conclusions drawn from these relations are that the histories of the continental shelves are directly related to the tectonic history of the adjacent continent. There is, incidentally no such thing as the " ideal " continental shelf in Australia (or any other continent) for it may be seen that there are shelves both of accumulation (the theory of MURRAY 1885) and of erosion (as postulated by VON RICHTHOFEN 1886), intergrading as compound shelves (as visualized by BUCHANAN 1887; FENNEMAN 1902; and DALY 1927), all distributed along one and the same continental margin, which would appear to have experienced a more or less connected structural evolution and been subject to a uniform eustatic history.

A second observation derived from these studies is that the deep-sea basins in turn seem to lie opposite the broad shelves and the continental basins, while the deep-sea ridges lie in the same trends as the Pre-Cambrian structural " grain " of the mainland. From this it may be concluded that *the features of the deep-sea floor are intimately related to those of the continent*, a point recently re-emphasized by HANS CLOOS (1948) and by LEES (1953).

It should be stressed that this conclusion refers specifically to the relations between the West Australian Shield and the eastern part of the Indian Ocean and should not be taken as a universal generalization. However, it is true that similar relations have been seen elsewhere, notably between Africa and its adjacent seas. KRENKEL (1925) made the earliest observations, and following publications of the detailed

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surveys of the *Meteor* Expedition (STOCKS and WÜST 1935), CLOOS (1937, 1948), investigated the geotectonic significance of these continental " felder " being reflected in the pattern of the ocean floor. CLOOS further claimed that these facts provided solid grounds for objecting to the idea of continental drift as envisaged by WEGENER in such regions.

At the same time it is desirable to point out that other sections of the ocean floor, e.g., the main India-Australian Basin, do not appear to possess this basic " felder " pattern of ridges and basins. Notably the central and southern parts of the Pacific Ocean (outside of the Andesite Line and its eastern marginal belt) lacks any such features so far as may be judged from the limited exploration data yet available.

GONDWANALAND PROBLEM

This is not the place for a detailed treatment of the problem of Gondwanaland, that " Atlantis " of the southern hemisphere which SUESS (1904-24) proposed as an explanation for the similarities in the geologic history, fauna and flora of the southern continents. Yet observations on the floor of the ocean separating the present continents are bound to bring up the question.

The present status of this theoretical macro-continent may be expressed as a point of view. Seen through the eyes of an observer residing in one of the southern continents, all the northern land-masses have much in common. In the same way, the southern lands have similarities so striking that SUESS thought that at one time they must have been connected. STILLE's " Norderde," or " Laurasia " of others, has many features which distinguish it from the " Süderde " or " Gondwana " continents. But this does not prove that one or the other was once a continuous land mass; it merely demonstrates a more or less common geologic history, at the same time, more or less distinct from that of the opposite hemisphere.

Many of the data, originally employed by SUESS, WEGENER, and others to demonstrate the uniformity of Gondwanaland have now fallen into disrepute. Most of the zoogeographic anomalies are now explained differently; the *Glossopteris* plants are now found to have winged spores, and so on.

Nevertheless, considerations of the geological history of the Indian Ocean suggest that its borderlands were continental for long periods. Two important gulfs, the Malgashe or Madasgascar Gulf on the west and the Westralian Gulf on the east, appeared during late Paleozoic times and widened during the Mesozoic. The first continuous marine connections around South Africa appeared during the Cretaceous with numerous small coastal transgressions. However, the first evidence of any close link from the west around the margin of southern Australia did not come until the Tertiary; TEICHERT (1951) recognizes Permian faunistic connections between Western Australia and Tasmania, but there is no evidence as to the route or location of this marine link.

The Mesozoic marine faunal developments of the Malgashe Trough, peninsular India and Westralian Trough, for similar environments, are naturally analogous, but they are sufficiently distinct that they may best be epxlained as being then as far apart as they are now. There is the granitic nature of the Seychelles (BAUER 1898) and possibly continental foundations of other parts of the north-western Indian Ocean (GLENNIE 1936) that speak against drift in that region.

The conclusion has therefore been reached by STILLE (1944, 1948) and also by the writer (1948) that the Indian Ocean is a " new ocean," one which owes its origin (at least in part) to the break-down of former continental crustal elements.

GEOTECTONIC CONSIDERATIONS

STILLE believed that the Indian Ocean was entirely a " Neuozean " (new ocean), but subsequently the writer's bathymetric-tectonic studies suggest that much of the large eastern basin may be underlain by primary oceánic crust (or " thalasso-craton "). Geological support for this concept has come in recent years from the discoveries of extensive Ordovician, Devonian and Carboniferous marine sediments in Western Australia (TEICHERT 1950; GUPPY and OPIK 1950), thus considerably antedating the Permian-Mesozoic marine history of the western side of the Indian Ocean. Such repeated Palaeozoic transgressions suggest a Paleozoic oceanic region in the east rather than a mere epicontinental gulf.

The term " thalasso-craton " (derived from the Greek *thalassa* = ocean; *kratos* = mastery or strength) is proposed by the writer to cover the concept of a part of the earth's strong, semi-rigid crust (" craton ") that underlies the primary or permanent ocean basins. This distinguishes such regions from the " hedreo-cratons " (of KAY 1951) that occupy the semi-rigid continental masses. These two distinct divisions of the earth's crust were first designated by STILLE (1934, 1944) as *Hochkratone* and *Tiefkratone*, but to avoid using terms of mixed linguistic roots, it seems best to employ the equivalents " hedreo-craton " and " thalasso-craton."

STILLE accepted the idea of the permanence of continents and oceans, only with reserve, however, recognizing that marginal parts of the hedreo-craton could subside in later cycles, being downwarped or downfaulted irregularly to oceanic depths. This process he named " Regeneration." Such a concept seems to fit well the data here presented for the marginal areas of the eastern Indian Ocean.

In complete contrast to these more rigid units, are the Mobile Belts (" Orogen " of KOBER) exemplified by the Indonesian Island Arcs on the northern side of our area. With their history of high mobility, seismicity, and vulcanicity, their vertical movements are of very different nature. Such belts one conceives as the granite-cored geosynclines of the future.

The regenerated areas may be regarded as transitional and of only semi-mobile character. It seems appropriate to distinguish them as the " Intermediate Areas." Regenerated sections of the ocean, as shown above, seem to pass without abrupt boundary into the semi-mobile basins of the continent. Where visible and available for direct study, it is possible for the stratigrapher to classify such basins amongst those geosynclines which evolve tectonically with intermediate type structures (Saxonian or Germanotype of STILLE), but which do not reach the degree of mobility that results in granitization or plutonic injection.

The term " parageosyncline " (STILLE) is appropriate to such basins. It was first used by SCHUCHERT (1923) in a somewhat different sense, but was never adopted into the literature. The term was redefined by STILLE (1935, 1936) to cover all those basins of sedimentation with semi-mobile to semi-rigid (i.e. well consolidated) basements, characterized by Saxonian or " Germanotype " tectonics; thus they are in in contrast to orthogeosynclines with their highly mobile basements and "Alpinotype" tectonics. KAY (1942) has discussed these terms, and introduced (1951) a series of new ones (exo-, zeugo-, auto-, paralia-, taphro-geosyncline, etc.) to cover the varied types of basin with semi-rigid basements. He did not adopt " parageosyncline " as a general term for them, out of respect for SCHUCHERT's priority. However, as a group term is urgently needed here and SCHUCHERT's usage was never employed by geotectonicists, there is a strong case for adopting STILLE's term, which is already widely employed in Europe.

It is apparent, therefore, that if the marginal parts of the Indian Ocean have been formerly continental, they must have subsided. They must accordingly occupy the role of parageosynclines, a complex belt of intermediate mobility lying midway between the highly rigid thalasso-craton of the Indian Ocean and the equally rigid hedreo-craton of the Australian continent. To the north, the thalasso-craton is separated from the hedreo-craton of South-East Asia by the orthogeosynclinal Mobile Belts of the East Indies. In both cases the oceanwards transition from the belts of increased mobility into the thalasso-craton appears ill-defined and gradual.

By analogy with geologically explored geosynclinal belts, it seems probable that both orthogeosynclinal and parageosynclinal belts possess a basement of inhomogeneous sialic character. In contrast the thalasso-cratonic basement, judging from the nature of associated volcanic rocks, must be essentially simatic. Geophysical data may shed some light on this aspect in the Indian Ocean, as may be seen from the next section.

GEOPHYSICAL DATA

Outside of the East Indian island arcs and associated oceanic trenches, the natural seismicity of the eastern part of the Indian Ocean is of a very low order. This is equally true for the adjacent parts of continental Australia. GUTENBERG and RICHTER (1949) lists only four ocean or shelf-margin shocks for the entire area under discussion (excluding, of course, the East Indies), and there is no change in the 1954 edition. Accordingly, local earthquakes may be of little help in determining the nature of the earth's crust just here.

Long-range determinations of Rayleigh-type waves may, however, be instructive. EWING and PRESS (1952) have shown that Rayleigh waves emanating from an earthquake in the Solomon Islands and recorded at a series of points on a great circle around the earth would pass through Australia, the Indian Ocean, South Africa, the Atlantic, North America and the central Pacific. When allowance is made for the known continental sectors of the course, the oceanic portion could be accounted for by assuming a water layer resting on a homogeneous simatic rock of 7·9 km/sec compression velocity. This is considered a fair mean for the thalasso-craton, which is known to be underlain by a layer of 6·8 resting at the Mohorovicic discontinuity on one of 8·1 km/sec. This would imply that *all* ocean sectors along this great circle course were essentially thalasso-cratonic. However, owing to the scale involved and the single example used there still seems room for a certain proportion of ocean of intermediate character (that may have been formerly continental).

Some very interesting conclusions have also been reached from consideration of the earthquakes emanating from the Mid-Indian Ridge. GUTENBERG and RICHTER have long regarded this as part of a circum-African ring, continuous via the Crozet Ridge with the Mid-Atlantic Ridge. The topography and geology of the ocean floor to the interior, i.e. African side of that ring suggests more a continental origin. As

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the present writer noted above the exterior, certainly the eastern part (i.e. in the Indian Ocean) suggests a thalasso-craton.

Results are still incomplete but a study of P-waves originating in the Mid-Indian Ridge earthquakes by Father POISSON (1950) at the Tananarive (Madagascar) seismological station, showed several seconds delay in reaching the African shore than in getting to the station in Western Australia. This interesting anomaly, if confirmed, would imply a notably different crustal structure east and west of the Mid-Indian Ridge, is as already implied by the topography (ROTHÉ 1951, 1954).*

Up until the present time, the only oceanographic expedition into the area employing seismic refraction surveys, has been that of the H.M.S. *Challenger* (II) in 1952 (see preliminary notes by GASKELL 1954; GASKELL and ASHTON 1954). This traverse was restricted to the northern part but serves to show the existence of a thalasso-cratonic crust. This is what GASKELL calls a " Type A " crust, characterized by a deep Pacific type profile, that is, about ½ km of sediment, 5 km of crust 6·5 km/sec velocity (generally regarded as indicating a simatic composition), reaching the Mohorovicic discontinuity and 8·1 km/sec velocity at about 11 km below sea-level.

A number of oceanographic gravity stations were established in 1935 by VENING MEINESZ (1948) on the Dutch submarine K-XVIII. Most important for our area was the traverse made following the western margin of Australia from Fremantle-Java, crossing most of the structures described in the first part of this paper. VENING MEINESZ has remarked on the universality of a remarkable gravity anomaly over continental margins, but this traverse is parallel to that margin. Notable negative isostatic anomalies were determined at stations 717 and 716 (over the Pilbara Rise), while a positive swing was established at station 715 over the Cuvier Basin. Their course was set too close to shore in the latitude of the West Australian Ridge, so no indication of this was recorded. It was observed, however, that an E-W profile over the West Australian Basin presented the usual deep-sea picture of no appreciable anomaly.

CONCLUSIONS

The conclusion we may reach from these, admittedly sparse, data is that the crust beneath the Indian Ocean is not all of one character, being marginally continental in origin. Further, in contrast to the belief of this writer in 1948, the ocean is not all of " juvenile " origin, but has a notable " core " of great antiquity, a thalasso-craton of Pacific character. It does not extend right to the margins of the Western Australian Shield which would appear to have been broken down in the course of post-Cambrian time along a belt up to 400 or 500 miles wide.

In considering a thalasso-craton of Pacific character, it is alomst inevitable to think at the same time of island arcs. In this instance it becomes understandable that the Burma-East Indian arcs should *face* the north-eastern Indian Ocean in its deepest sector.

ACKNOWLEDGMENTS

The writer is happy to acknowledge the helpful discussions and correspondence with RUSSELL RAITT, GUSTAV ARRHENIUS, H. W. MENARD, CURT TEICHERT, F. A.

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* GUTENBERG and RICHTER (personal communication) have indicated to the writer that these results are very uncertain owing to inaccuracies of epicentre location, so the case must be marked " unproven " as yet, (R.W.F.)

VENING MEINESZ, H. H. HESS, J. TUZO WILSON, J. P. ROTHÉ, F. PRESS and others. Also the facilities provided by ROGER REVELLE at the Scripps Institution, when the writer was visiting the United States with the assistance of a FULBRIGHT Grant.

Contribution from the Scripps Institution of Oceanography, New Series No. 742.

Scripps Institution of Oceanography, La Jolla, California; and University of Western Australia, Nedlands, W.A., Australia.

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⁂ Unfortunately this paper went into print before the British National Committee on the Nomenclature of Ocean Bottom Features, to which DR. FAIRBRIDGE had addressed himself for an opinion, had met to consider the naming of the deep-sea features to which he refers above. The Committee met on 26 November and came to the conclusson that the names Leeuwin Sill, Christmas Rise, West Australian Ridge, Cuvier Basin, North Australian Basin, West Australian Basin and Exmouth Ridge, would require further consideration.—C.D.O.

Contributions from Scripps Institution of Oceanography,
New Series No.742

Printed in Great Britain by The Salisbury Press Ltd., Publicity House, Wilton Road, Salisbury, Wilts. (89854)

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(*Reprinted from Nature, Vol.* 174, *p.* 869, *November* 6, 1954)

SUBMARINE ILLUMINATION AND THE TWILIGHT MOVEMENTS OF A SONIC SCATTERING LAYER[*]

By ELIZABETH M. KAMPA and BRIAN P. BODEN
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IT has long been recognized that many zooplankton organisms exist in distinct strata during the day and that they may undergo extensive diurnal vertical migrations. The similarity of their behaviour to that of certain sonic-scattering layers in the sea, observable with echo-sounding equipment, led Johnson[1] to suggest that the origin of these layers is biological. Collections by various methods have shown that concentrations of both zooplankton and fishes are associated with these layers. Although much thought has been devoted to the composition of the layers and to the acoustic properties of the animals probably comprising them, attention to the causes of

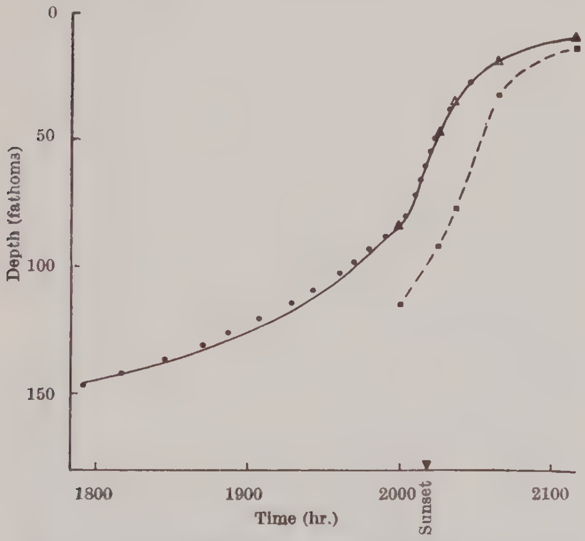

Fig. 1. Evening ascent of a scattering layer and of the $6 \cdot 6 \times 10^{-4}$ foot-candle isolume. Solid line represents top of layer as seen on *NMC*-1 fathometer record, round dots represent measured positions of the isolume, triangles represent scattering at 9·6–20 kc./s.; solid squares (– – – –) represent scattering at 2·4–3·4 kc./s.

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[*] Contribution from the Scripps Institution of Oceanography, New Series, No. 743.

their vertical migrations has been restricted to speculation and to laboratory experiments with individuals.

As a first step in determining these causes, the change of depth of a certain level of submarine illumination during twilight is compared here with the depths of a certain scattering layer during its vertical migration.

Intensity of illumination at depth was measured with a submarine photometer designed expressly for this purpose by James M. Snodgrass, of the Special Developments Division at the Scripps Institution of Oceanography. This instrument, described previously by Kampa and Boden[2], employs an *RCA 931A* photomultiplier tube which is sensitive to wavelengths between 300 and 700 mμ. The sensitivity has a sharp peak at 400 mμ and drops to 50 per cent at 320 mμ and 518 mμ. The tube is protected against pressure at depth by an oil-filled glass riding-light cover which makes water-tight contact with the brass cylinder containing the submerged portion of the photometer circuit.

The photometer was calibrated with a Weston illumination meter using a 100-watt *G.E.* projection bulb at 115 volts.

During the observations reported here, the submerged unit was rigged in such a way that the sensitive surface of the photomultiplier tube was vertical, favouring measurement of horizontal illumination.

When a curve of equal illumination was to be determined for comparison with scattering layer position during vertical migration, the submerged unit was lowered to the depth of the top of the layer, and the light intensity and time were recorded. This time was noted on the fathogram as well. The photometer was then either raised (sunset) or lowered (sunrise) 10 m. and held at the new position until meter readings showed that the illumination intensity was the same as that previously observed. The time was again recorded. This process was repeated until the fathogram showed that the scattering layer position had become relatively constant, either at the surface or at depth.

Scattering layers were observed with an *NMC*-1 fathometer operating at 17·5 kc./s. A more detailed analysis of the scattering properties of these layers was effected by a multiple-frequency technique similar to that employed by Hersey, Johnson and Davis[3]. The wide-band sound source in this analysis was a half-pound block of TNT detonated at the surface about 30 m. from the receiver. The receiver was a directional Rochelle salt hydrophone directed

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vertically downward just below the surface at the side of the ship. Sounds received by hydrophone were recorded with a 'Magnecord' 63*AH* tape-winder with *PT*7-*P* 'Magnecord' amplifier adapted to operate at 30 in. per sec. The record of echoes from each explosion was filtered through an H. H. Scott Type 420-*A* sound analyser, and an oscillographic record was made of the reverberation at various frequencies using a triggered single-sweep oscillograph fitted with a 'Polaroid' Land camera.

Biological collections were made from each layer under observation with a 1-m. plankton net of 8 ××× bolting silk. This net could be opened and closed at depth by means of the Leavitt[4] opening and closing device. A time–depth recorder was incorporated in the collecting gear to give a record of the fishing depth of the net. After superficial examination these collections were dark-adapted in running sea water and then deep-frozen. A report of the light-sensitive substances obtained from these animals will be presented shortly.

Fig. 1 shows the twilight ascent of a scattering layer in the San Diego Trough on June 30, as well as the ascent of the level of illumination ($6\cdot6 \times 10^{-4}$ foot-candles) with which this scattering layer had been associated during the afternoon. It can be seen that the ascending scattering lags behind the ascending light intensity between 1830 and 1950 hours (P.D.T.).

This layer was observed to split into two components during its migration. A similar splitting of

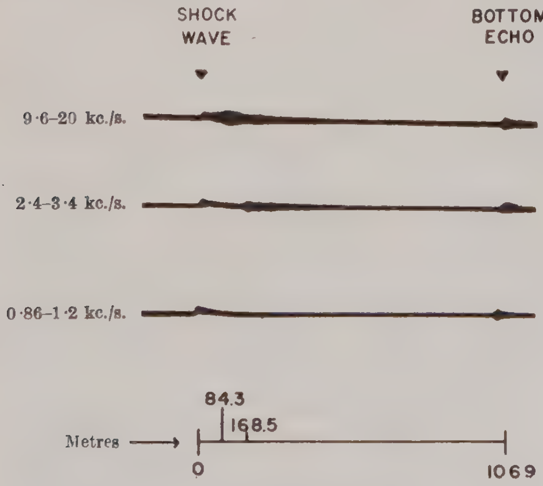

Fig. 2. Oscillogram showing back reverberation at selected frequency pass-bands. Peaks of scattering can be seen at 84·3 and 168·5 m.

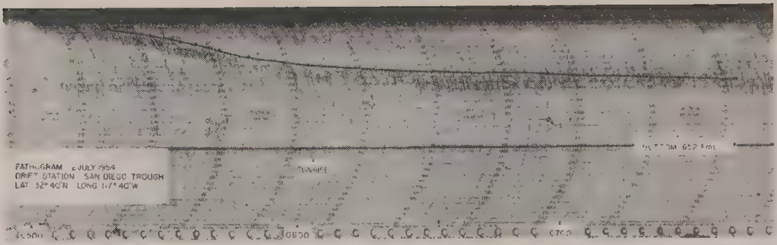

Fig. 3. Fathogram of layer descending in the morning. The $5{\cdot}9 \times 10^{-5}$ foot-candle isolume is superimposed

the single layer during ascent was observed on the following evening when the multiple-frequency technique was employed (risk of damage to the light meter precluded its use while TNT was being detonated). Fig. 1 also shows the ascent of this split layer on July 1. The upper component of the split layer scattered relatively high frequencies (9·6–20 kc./s.), whereas the lower component scattered only lower frequencies (2·4–3·4 kc./s.). Fig. 2 shows oscillograms of reverberations from the second TNT explosion in the July 1 (Fig. 1) series. The upper component, scattering at higher frequencies, is apparent at 84·3 m. (46·1 fathoms), while the lower component is at 168·5 m. (92·4 fathoms).

Fig. 3 is a fathogram made in the San Diego Trough on July 2 during morning twilight to sunrise. As soon as a scattering layer could be observed breaking away from surface scattering, the photometer was lowered to the top of the layer. The intensity of illumination here was $5{\cdot}9 \times 10^{-5}$ foot-candles. The descent of the $5{\cdot}9 \times 10^{-5}$ foot-candle isolume is superimposed on the fathogram. It can be seen that the descending layer and the isolume enter and continue through a layer which had persisted through the night at about 135 fathoms.

The extremely close correlation between the vertical movements of a scattering layer and those of a constant level of illumination (Figs. 1 and 3) argues strongly that the migrations of these layers are simple responses to variations in environmental light intensity. The slight lag in the ascent of the layer behind that of the isolume (Fig. 1) during the early part of the migration suggests that, although 0·00066 foot-candles may constitute an optimum illumination for the scatterers, the threshold intensity for migration is slightly lower. This threshold was reached apparently at about 1900 hours, and the scatterers increased their rate of ascent. Shortly before sunset the layer overtook the isolume, and, at sunset when the ascent is most rapid (about 2·75 fathoms per minute), the rates of ascent of illumination-level and scattering layer are identical.

It is interesting to note that the illumination intensity ($5{\cdot}9 \times 10^{-5}$ foot-candles) with which the descending layer (Fig. 3) was associated on July 2 is less than one-tenth of that determined for the ascending layer on June 30 ($6{\cdot}6 \times 10^{-4}$ foot-candles). Assuming that these layers were similar in biological composition—an assumption which was borne out by collections taken from them—it seems that during the moonless night the animals became dark-adapted and consequently more sensitive to lower light intensities. The extent to which various degrees of dark- and light-adaptation influence the position of the scatterers relative to illumination-level demands further investigation.

Frequency analysis, at the time the fathometer has revealed the splitting of a layer during ascent, shows that the upper component, which seems to be responding to a photic stimulus, scatters sound at 9·6–20 kc./s., whereas the scattering peak of the lower component is at 2·4–3·4 kc./s. This is evidence that the upper part of the layer may be comprised of smaller organisms (invertebrates ?) and the lower part of larger ones (fish ?).

Thus we have the picture of a heterogeneous layer existing during the day at an illumination intensity which is optimum for one or more animals associated with the layer. During the evening twilight this organism ascends with its optimum intensity and is followed by predators which have been in the layer during the day. This contention is supported by the results of Tucker[5], whose analysis of net hauls taken in the layer led him to conclude that invertebrates (euphausiid crustaceans) were the dominant organisms in the upper part of the layer, while fish were dominant in the lower part of the same layer. Rigidly controlled biological collections from different components of the layer during vertical migration promise to do much in elucidating which organisms are responding to light and which are merely following a migrating food source.

This work is being conducted under contract between the Geophysics Branch of the Office of Naval Research and the Scripps Institution of Oceanography, University of California. [Aug. 7.

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Printed in Great Britain by Fisher, Knight & Co., Ltd., St. Albans.

Reprinted from *The Luminescence of Biological Systems*, Frank H Johnson, Editor, published by the American Association for the Advancement of Science, Washington, D.C., 1955.

Bioluminescence in *Gonyaulax polyedra*[*]

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Gonyaulax polyedra is a photosynthetic marine dinoflagellate which is occasionally responsible for striking luminescent displays in the coastal waters of Southern California. The individual cells are armored; they are polyhedral in shape, 45μ long and 41μ wide and contain a heavily pigmented brown protoplast, in which the chlorophyll is masked by an abundance of carotenoid pigments.

The unialgal culture of *Gonyaulax polyedra* investigated was started from net samples collected off Scripps Pier on September 22, 1952. Since that time, the organism has been maintained in aged sea water, diluted to 75% of full strength with twice-distilled water, and supplemented with $2 \times 10^{-3} M$ KNO_3, $2 \times 10^{-4} M$ K_2HPO_4, $6 \times 10^{-6} M$ $FeCl_3$, $6 \times 10^{-7} M$ $MnCl_2$, ethylene diamine tetracetic acid (EDTA), 10 mg per liter, and 2% soil extract. Liquid flask cultures were grown either at room temperature in a window with a northern exposure, or at 20° C under continuous illumination from white fluorescent lamps, at an intensity of about 700 foot-candles. Growth was about equally good in full-strength and half-strength sea water, or in media in which the supplementary salts were reduced to one-half the above values.

Soil extract was required for growth in aged sea water and could not be replaced by vitamin B_{12} alone. No growth, however, was obtained in artificial sea water supplemented with soil extract. At 20° C, maximum rate of growth was obtained at 500–800 foot-candles. The generation time was 56 hours (0.43 division in 24 hours), and the maximum cell densities were 30,000–50,000 cells per milliliter.

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Photosynthesis of *Gonyaulax* cell suspensions was measured in artificial sea water (formula of Emerson and Green, 1934, modified to contain one-fourth the normal amount of Ca and Mg) by the direct manometric method. In saturating light (800 ft-c) at 20° C and non-limiting CO_2 concentration, as provided by 0.0234 *M* bicarbonate – 0.0016 *M* carbonate buffer, the rate of photosynthetic oxygen production was as follows (corrected for respiration): 350 mm^3 $O_2/hr/10^6$ cells; 14,800 mm^3 $O_2/hr/g$ solids; 5000 mm^3 $O_2/hr/mg$ chlorophyll *a* plus *c*, estimated by the equations of Richards (1952). Under these conditions, the rate of oxygen production was about 5 times that of respiratory oxygen consumption. The temperature optimum for photosynthesis in *Gonyaulax* is about 30° C.

Gonyaulax has retained the ability to luminesce in culture for 1½ years. Light is emitted on mechanical stimulation as a bright bluish-green flash of short duration. Stimuli repeated at intervals of one minute elicit progressively weaker responses. Since preliminary observation with dark-adapted eyes indicated that luminescence of cell suspensions exposed to light was considerably weaker than those darkened for a few hours, a study was undertaken of the effect of light on the luminescence of this organism. The apparatus employed for measuring and recording light emission included a photomultiplier tube (931A) and appropriate amplifying circuit, with variable sensitivity, coupled to a Speedomax recorder. Insertion of a condenser in the circuit served to slow down the instrumental response and to provide smooth curves for convenience in planimetric calculations of total light emission.* Aliquot cell suspensions of 3 ml were taken from mature cultures (20,000–40,000 cells per milliliter) grown at 20° C in constant light of 700 ft-c. The aliquots were held in the lighted incubator for 4 hours and then placed in darkness. Measurements of light emission by different aliquots were made at intervals during the dark adaptation period. Luminescence, stimulated by passing a stream of air through the cell suspension at a constant rate of flow for one minute, rose sharply to a maximum in less than 7 seconds (less than a second when measured with a faster recording device) and decreased to a low steady state.

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* This apparatus was designed by Mr. James Snodgrass, Division of Special Developments, Scripps Institution of Oceanography.

Cell suspensions taken directly from the lighted incubator luminesced only slightly on stimulation. When such cells were placed in darkness, the capacity for luminescence increased with time in darkness and reached a peak after 6–8 hours, as shown in Fig. 1. With the time in darkness further increased, luminescence decreased progressively, reaching a low value after 15–18 hours. This decline was followed by a second increase in light emission, which reached a peak after 28–30 hours in darkness. The second peak was lower than the first and was followed by a second decrease in luminescence. This

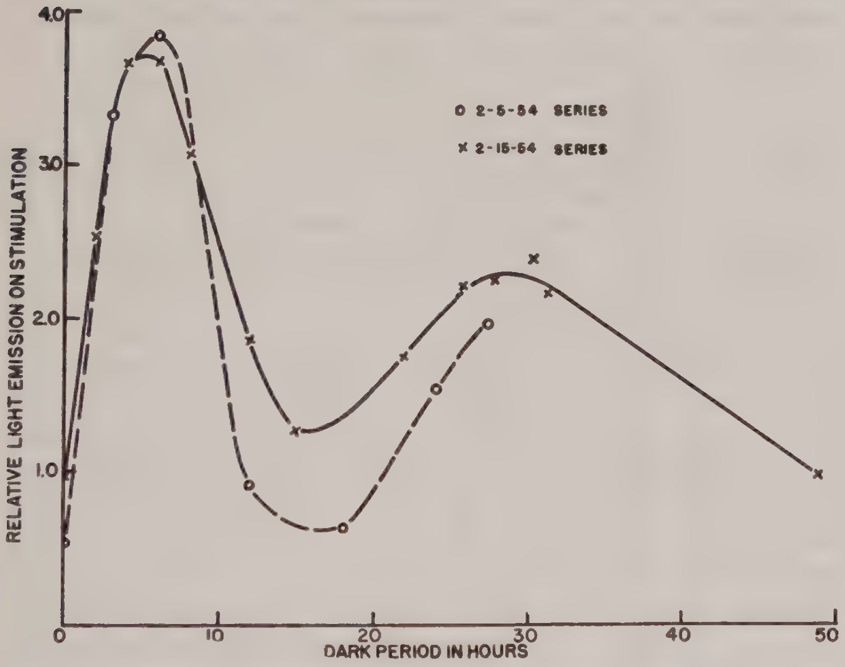

FIG. 1. Variation in luminescence of *Gonyaulax polyedra* cell suspensions with time in darkness, after growth in white light at 700 ft-c. Each measurement represents the integrated light emission during mechanical stimulation of one minute duration by different aliquots, not otherwise agitated until the indicated time.

fluctuation pattern in luminescence has been observed a number of times and appears to be independent of the time of day at which cultures are placed in darkness. Instrumental fluctuations and variations between duplicates were of the order of 2–4% and could not account for the changes observed.

Cell suspensions placed in white light after an optimum dark adaptation time (5–6 hr) showed a progressive decrease in luminescence

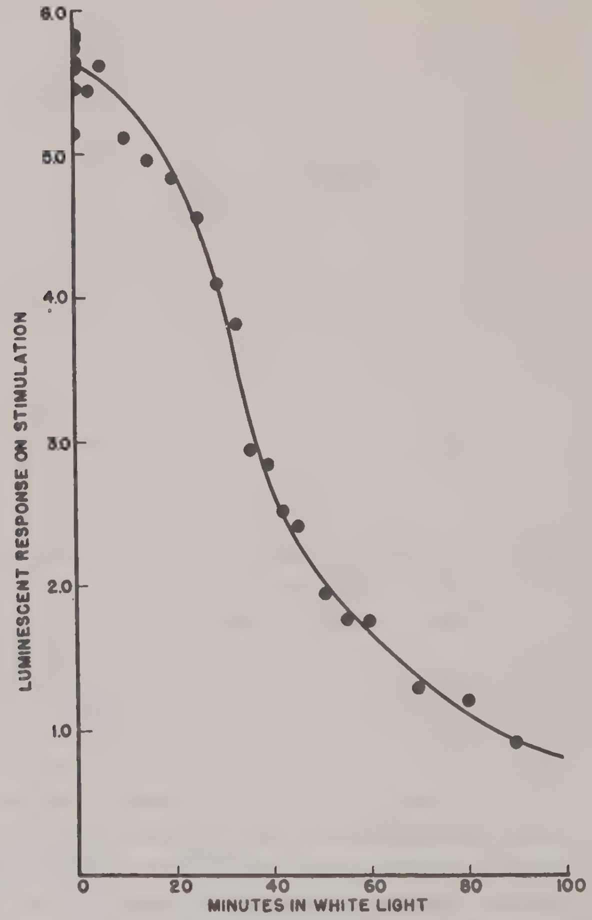

FIG. 2. Decrease in luminescence of *Gonyaulax polyedra* suspensions upon exposure of dark-adapted cells to 700 ft-c white light. The cells were grown in the light and placed in darkness for 6 hours prior to irradiation. Relative light emission prior to dark adaptation was 0.75.

with time of irradiation (Fig. 2). When exposed to fluorescent light of 700 ft-c intensity, maximum inhibition of luminescence was obtained in 90 minutes, the final level of light emission being about equal to that of cultures maintained continuously in the light. Preliminary experiments with broad band pass filters intercepting the fluorescent light indicate that the blue-violet end of the spectrum is the most effective in suppressing luminescence. There is a suggestion of a small effect of red light, and a more detailed determination of the effectiveness spectrum is planned.

The inhibition of luminescence by light in *Gonyaulax* suggests a photooxidation of one of the components of the luminescent system, as in luminous bacteria and *Cypridina* extracts. The observation that the maximum light emission of dark-adapted cultures increases with the duration of the previous photosynthetic period implies that light exerts a second effect on luminescence, probably through the building up of photosynthetic products or intermediates necessary for the maintenance of the luminescent system. The decline in luminescence capacity in the dark observed during the period 8–18 hours (Fig. 1) may be interpreted as a progressive depletion of these substances. It has been suggested that, as starvation proceeds, degenerative processes within the cell result in the release of additional reserves and lead to the second peak observed in darkened cells. The final decline in luminescence after 30 hours is associated with loss in cell viability and death. This undoubtedly results from starvation, since *Gonyaulax* is nutritionally dependent on photosynthesis.

The above findings recall earlier reports (cf. Harvey, 1952) based on visual observations that natural populations of dinoflagellates show fluctuations in luminescence when brought into the laboratory. In unialgal cultures of *Gonyaulax polyedra* maintained in the laboratory, luminescence is partially suppressed by exposure to bright light. The ability to luminesce on stimulation is enhanced in darkened cultures, and subsequently falls and rises before the cells die of starvation.

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ON THE HISTORY OF THE OCEANS[1]

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I shall discuss two problems concerning the history of the ocean: (1) The volume of water on the earth's surface at different times in the past. (2) Former conditions in the water and in the overlying atmosphere compared with those existing today. Specifically, we may ask whether the waters were acid, or slightly alkaline as at present, and whether conditions were oxidizing or reducing, that is, whether or not free oxygen was present.

Much of the discussion is not original. It owes a good deal to the flashing insight of Harold Urey, who was among the first to apply the principles of chemistry to the problems of the early history of the earth and the solar system; to the skillful observations of Gerard Kuiper, who has described in quantitative detail the atmospheres of planets other than our own; and to the careful analysis of William Rubey, who has marshalled the facts of geology to throw light on the broad questions we are discussing.

The scarcity of the noble gases (neon, xenon and krypton) in the earth, compared with their cosmic abundance, shows that these gases were driven away from the earth at some time in its early history. Other gases of comparable molecular weights must therefore have escaped also if they were not held in some kind of chemical or physical combination (Brown, 1952). Thus, in this respect the atmosphere and the ocean must be secondary. The ocean waters did not condense from a primitive hot and heavy atmosphere but were squeezed out of the interior of the earth. But the rare gases probably escaped from the "protoplanet" before the earth achieved its present size and degree of compaction (Kuiper, 1952: 320–324). We may ask, then, did the squeezing out of the water and of the atmospheric gases take place mostly before the geological record began or have the atmosphere and the ocean slowly grown throughout geologic time?

During the past 50 years geologists have expressed diverse views on this question. Some advocate the doctrine of permanency, that

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[1] Contribution from the Scripps Institution of Oceanography, New Series No. 745.

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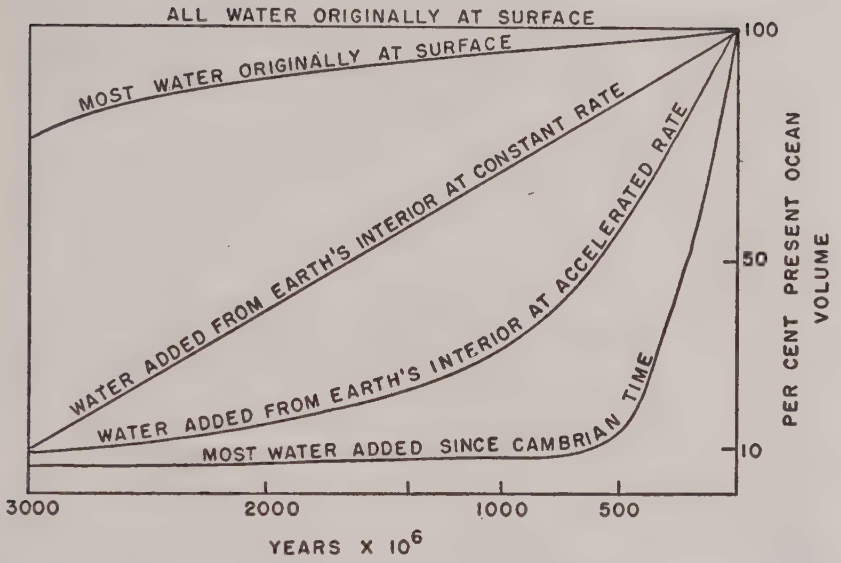

Figure 1. Possible volumes of the ocean during the geologic past, according to different hypotheses.

ever since the beginning of the geologic record the volume of ocean waters has been about the same as that which exists at present; others claim that in the earliest Archaeozoic the ocean volume was probably less than 10% of what it is today (Fig. 1).

Those (for example, see Rubey, 1951) who have argued for the slow growth of the ocean have shown that the quantity of water now flowing from volcanic springs is more than sufficient, if extrapolated back through geologic time, to account for all the water in the ocean. Furthermore, they have pointed out that in volcanic gases and in igneous rocks the ratios of the "volatiles" (water, carbon dioxide, chlorine, nitrogen, and sulphur) are similar to the ratios in the ocean, atmosphere and sedimentary rocks combined. The total amounts of these substances present on the earth's surface are roughly equivalent to the amounts contained in a layer of igneous rocks only 50 to 100 km thick, so that a relatively small loss of certain of the volatiles in igneous rocks would be sufficient to account for the amounts on the surface.

If the volatiles other than water were present to more than a minor extent at the beginning of geologic time, the earliest sedimentary rocks should be different in several respects from those laid down since. We do not believe this is the case. For example, with all the carbon dioxide present initially, the rate of chemical weathering should have been enormous and the earliest sediments should be characterized by a higher than observed percentage of limestones. Moreover, if chlorine and sulphur existed in their present amounts and were not balanced against metal ions, the primeval ocean should have been acid but should have quickly attained through chemical weathering its present salt content. A difficulty then arises in accounting for the apparently continuous partition throughout geologic time of the sodium of igneous rocks between sedimentary rocks and the ocean.

Other evidence for a slow outflow of volatiles comes from the presence of appreciable amounts of helium 4 and argon 40 in the earth's atmosphere. These are almost entirely radiogenic, from decay of the uranium and thorium series and of potassium 40; the amounts in the atmosphere, particularly the presence of 10 to 20% of all the argon ever produced in the crust and mantle of the earth, suggest that other volatiles could also have flowed out of the earth's interior in large quantities (Birch, 1951; Kulp, 1951).

There is evidence that the present continents have grown laterally throughout geologic time (Wilson, 1954). For the most part, the oldest rocks are concentrated in the central shield areas, with younger rocks around their edges. If the growth of the continents has included the greater part of their present areas, the area occupied by the ocean has been considerably reduced and the sea floor must have become deeper relative to the continental level. Isostasy would require a thickening of the continental crust, and this profound redistribution of the earth's materials could very well have been accompanied by an outward flow of water, which would have deepened the ocean still further.

Geologists (for example, see Kuenen, 1950) who believe in the permanence of the oceans have pointed out that the water contained in the total volume of volcanic rocks produced during geologic time is far less than the volume of water in the oceans. The volatiles other than water may have slowly seeped from the interior of the earth through volcanic springs and in other ways while the water itself may have simply recirculated in the upper part of the crust (Conway, 1942). The chemical mechanism by which the water contained in igneous rocks could have been released is not clear. All the atmospheric argon may have appeared in the atmosphere in pregeologic time, because the rate of production was then much higher (Birch, 1951). However, this cannot be true of the helium 4 now present in the atmosphere, because it is known from the ratio of helium 3 to tritium (Libby, 1946) that helium escapes from the atmosphere

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at such a rate that virtually all the helium initially present must have escaped.

Light may be thrown on this question of the ocean's growth by a comparison of Earth with her sister planets, Mars and Venus. The earth has sometimes been called the water planet. To an observer on Mars the most striking feature of Earth might well be the beautiful pattern of sea and land, with the continents rising like varicolored islands from the world-girdling ocean. By contrast, to us Mars is dust dry; the total amount of water in its atmosphere is sufficient to form a liquid layer less than a tenth of a millimeter thick (Kuiper, 1952: 389). A Martian observer might also note another contrast between Mars and Earth. The earth's land surface is rough with great elongate ridges which we call mountain ranges, and the red flares of volcanic activity are frequently present. By contrast, the surface of Mars appears to us to be relatively smooth (Urey, 1952: 222); there are probably no high mountains, and as we shall see, little volcanic activity.

A careful Martian observer would also conclude, by comparing the speed of rotation of the earth with its oblateness, that the earth has a core of much heavier material than the surrounding shell. Probably he would not be able to recognize what we know from seismic evidence that this core is liquid. We believe, from a similar comparison of speed of rotation and oblateness, that if Mars has a core it must be small (Brown, 1950: 641).

It is possible that these differences between Earth and Mars are related and, if so, they may help us to reconstruct the history of our own ocean. The scarcity of water on Mars has often been attributed to photochemical dissociation and the escape of hydrogen and oxygen. Because of the smaller size of Mars, its escape velocity is only about half of that from the earth, and probably some oxygen as well as hydrogen, produced by the photochemical dissociation of water, have been lost. As I shall attempt to show, however, Mars may never have had much water on its surface.

To examine this question further, let us take a more detailed look at the composition of the volatiles of Mars, Venus and Earth. Table I shows what is known about the amounts of water, carbon dioxide, oxygen, nitrogen plus argon, methane and sulphur dioxide on the surfaces of these terrestrial planets. The total mass of atmospheric gases per unit area on Mars is about 20% of that on the earth. Of this Kuiper (1952: 388) believes that perhaps 96% is nitrogen and nearly 4% argon. There is about twice as much carbon dioxide per unit area as that in the terrestrial atmosphere. Oxygen has not been detected, and, according to Dunham (1952: 299), the amount in the atmosphere is less than 0.35 g cm^{-2}. To this should be added

TABLE I. SURFACE VOLATILES ON EARTH, VENUS AND MARS* IN G CM^{-2}. NUMBERS OUTSIDE PARENTHESES INDICATE AMOUNT IN PLANET'S ATMOSPHERE. NUMBERS IN PARENTHESES INDICATE ESTIMATED TOTAL AMOUNT IN ATMOSPHERE, HYDROSPHERE AND SEDIMENTS

Substance	*Earth*	*Venus*	*Mars*
H_2O	6.25	<0.12	0.01
	(3.15×10^5)		(0.1)
CO_2	0.46	210	0.92
	(1.8×10^4)		
O_2	232		
	(1430)	<4.5	<0.35
			(50)
$N_2 + A$	770	?	190
	(850)		
CH_4	9.4×10^{-4}	<0.015	<0.008
SO_2+$SO_4^{=}$	10^{-9}	?	$<3 \times 10^{-9}$
	(10^3)		

* Values for Earth principally from Hutchinson (1954); for Mars and Venus from Kuiper (1952), Dunham (1952), and author's estimate of amount of oxidized iron.

the amount used in oxidizing ferrous iron to ferric iron in the surface rocks. This amount can be estimated in the following way: Assume that 10% of the planet's surface was once covered with mountains of impact origin, like those on the moon, and that the average height of these mountains was 1000 m. During the lifetime of the planet these mountains could have been leveled by wind erosion, leaving a layer of eroded material. If the mountains were conical in shape and if the eroded material was originally similar to the average terrestrial igneous rock in our continental crust, the eroded layer must be about 25 m thick, its density must be 2.7, and 8 g O_2/kg would have been required to oxidize the contained iron, or 50 g cm^{-2} over the planet's surface.

Less than 0.01 g cm^{-2} of water is present in the Martian atmosphere. The polar snow caps probably contain an amount of water equivalent to about 0.1 g cm^{-2} when spread out over the planet's surface (Kuiper, 1952; 397).

Neither methane nor sulphur dioxide have been detected on Mars, even though the methods of analysis (ultraviolet and infrared spectroscopy) are quite sensitive. The absence of sulphur dioxide in a virtually water-free atmosphere suggests the absence of vulcanism (Kuiper, 1952: 367). We will discuss the significance of the absence of methane later.

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On Venus, neither water nor oxygen have been found; according to Dunham (1952: 295), the amounts present are less than 2% of those in the earth's atmosphere. The principal gas is carbon dioxide, which is present in large amounts. This fact in itself indicates the absence of water. In the presence of water, the tendency to approach the "Urey Equilibrium,"

$$\mathrm{Mg\,SiO_3 + CO_2\,(g) \leftrightarrows Mg\,CO_3 + SiO_2} \quad \text{and}$$

$$\mathrm{Ca\ SiO_3 + CO_2\,(g) \rightleftarrows CaCO_3 + SiO_2}\ ,$$

would quickly result in the production of carbonates and in the depletion of the atmospheric carbon dioxide (Urey, 1952: 148–149). As on Mars, the absence of methane is noteworthy. The amount of nitrogen plus argon is not known, but it may be quite large. These gases cannot be detected spectroscopically and their presence on Mars is inferred from other observations.

If Mars originally had an appreciable quantity of water and nitrogen, but no oxygen, on its surface and in its atmosphere, then some solar ultraviolet radiation should have penetrated to the surface and some water would have been dissociated photochemically into hydrogen and oxygen. The hydrogen would escape rapidly from the planet, the oxygen much more slowly, at a rate determined by the temperature in the Martian exosphere. Some oxygen would also be withdrawn from the atmosphere by oxidation of iron in surface rocks. The oxygen remaining in the atmosphere would absorb the ultraviolet radiation before it reached the planet's surface. Further dissociation of water would then be confined to the outer region of the atmosphere. Just as on Earth, there should have been at least one and perhaps two atmospheric layers of very low temperature, between 150° and 200° K. Harteck and Jensen (1948: 591) and Kuiper (1952: 310–314) have pointed out that on Earth these low temperature layers and the overlying layers of increasing temperature act as a "cold trap" through which water can pass only very slowly. Kuiper has estimated that the rate of flow of water through the stratospheric cold trap on Earth is 1.4×10^{-14} g cm^{-2} sec^{-1} or 1.5 kg cm^{-2} in 3.5×10^9 years. He suggests that, because of the lower temperature in the corresponding atmospheric layer on Mars, the rate of outward flow of water is perhaps 100 times slower. In any case, the oxygen content of the Martian atmosphere should have increased rapidly to such an amount that a steady state equilibrium would exist between the rate of transfer of water to the upper atmosphere and the rate of escape of oxygen from the exosphere. This equilibrium may well exist at the present time. Dunham's (1952) upper limit for oxygen in the Martian atmosphere, 0.35 g cm^{-2} (Table I), is about 50 times the amount of oxygen required in the earth's atmosphere to absorb solar radiation with wave lengths between 1800 and 2000 angstroms (Goldberg, 1954: 748). Radiation of these wave lengths is responsible for photochemical dissociation of water in the outer layers of Earth's atmosphere (Bates, 1954: 591–592). Thus, photochemical dissociation of water may now occur only some tens of kilometers above the solid surface of Mars (Fig. 2).

Spitzer (1952: 239–244) has recently formulated the relationship between escape velocities for atmospheric gases and temperature in the exospheres of Earth and Mars. His results are confirmed as to order of magnitude by Libby's (1946: 671) essentially experimental determination of the rate of escape of helium 3 from the earth's atmosphere, based on the ratio of helium 3 to tritium. Table II, computed from Spitzer's equations, shows the times required at different exosphere temperatures for nitrogen and oxygen in the Martian atmosphere to decrease by 1/e. The escape time for nitrogen depends on the degree of dissociation of molecular nitrogen into the atomic form at the base of the exosphere. The percentage dissociation has been estimated as being between 0.01 and 0.001 by both Bates (1954: 589) and Nicolet (1954: 687). If we assume that the total amount of nitrogen ever present in the atmosphere of Mars is equal to the nitrogen now in the earth's atmosphere, the Martian exosphere temperature lies between 1300° and 1700° K (Table III). The actual value depends: (1) on whether all the nitrogen was originally present 3.5×10^9 years ago or has come from the interior during the planet's lifetime; and (2) on the ratio of molecular to atomic nitrogen in the exosphere. The range of escape times for oxygen over this tempera-

TABLE II. TIMES REQUIRED FOR NITROGEN AND OXYGEN TO DECREASE BY 1/e THROUGH ESCAPE FROM MARTIAN ATMOSPHERE, AT DIFFERENT EXOSPHERE TEMPERATURES

Temperature in °K at base of Martian exosphere	*Time of escape in years*		
	Nitrogen		*Oxygen*
	$N/N_2 = 0.01$	$N/N_2 = 0.001$	
1200	5.0×10^9	5.0×10^{10}	5.9×10^8
1300	1.7×10^9	1.7×10^{10}	1.5×10^8
1400	6.1×10^8	6.1×10^9	4.7×10^7
1500	2.5×10^8	2.5×10^9	1.7×10^7
1600	1.2×10^8	1.2×10^9	6.4×10^6
1700	5.9×10^7	5.9×10^8	2.9×10^6
1800	3.4×10^7	3.4×10^8	1.6×10^6

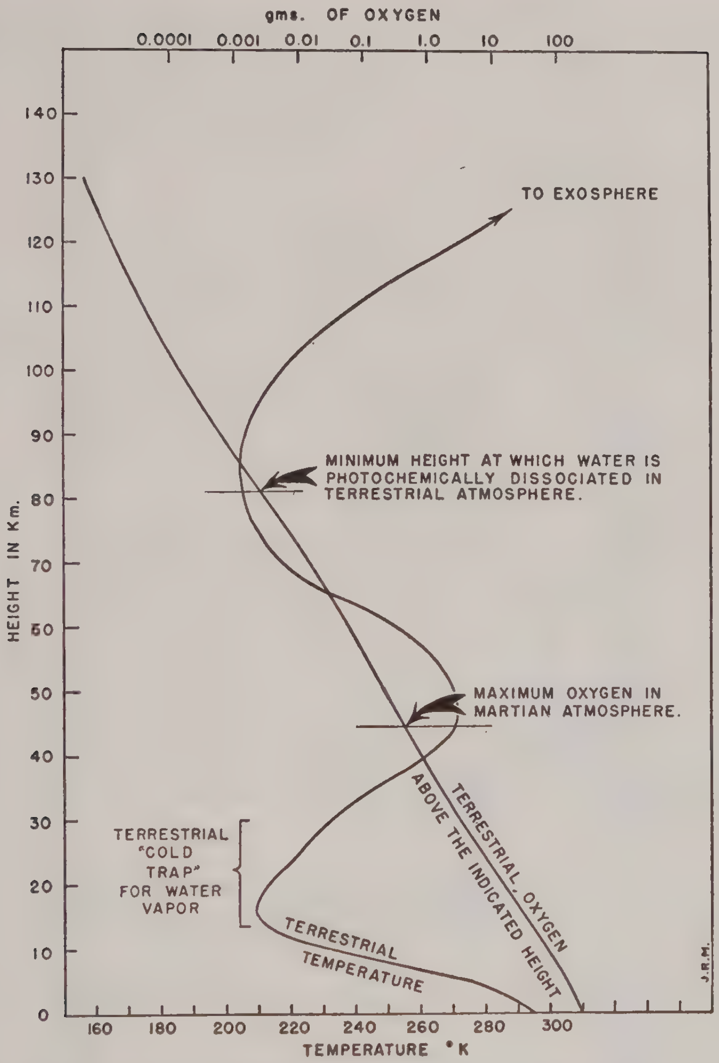

Figure 2. Temperature and oxygen content of the terrestrial atmosphere, showing the minimum height for photochemical dissociation of water, the "cold trap" for upward transport of water and the height above which the oxygen of the terrestrial atmosphere is equal to the maximum oxygen content of the Martian atmosphere.

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TABLE III. RATIOS OF TOTAL MARTIAN AND TERRESTRIAL NITROGEN AND WATER, PER UNIT AREA, DURING 3.5 × 10^9 YEARS, for DIFFERENT MARTIAN EXOSPHERE TEMPERATURES

Temperature at base of Martian exosphere, °K	$\frac{\text{Earth N}}{\text{Mars N}} = \frac{850}{\text{Mars N}}$				$\frac{\text{Earth water}}{\text{Mars water}} = \frac{3.15 \times 10^5}{\text{Mars water}}$
	All Mars nitrogen originally present on surface		*All Mars nitrogen derived from planet's interior at constant rate*		
	$N/N_2 = 0.01$	$N/N_2 = 0.001$	$N/N_2 = 0.01$	$N/N_2 = 0.001$	
1200	2.2	4.2	3.2	4.4	5.3 × 10^3
1300	1.5*	3.6	1.9*	4.0	4.8 × 10^3
1400	.13	2.6	.79	3.4	3.7 × 10^3
1500	10^{-5}	1.1*	.32	2.4	2.3 × 10^3
1600	10^{-12}	.27	.15	1.5*	1.2 × 10^3
1700	10^{-25}	.14	.076	.76	5.9 × 10^2
1800	10^{-44}	2 × 10^{-4}	.043	.43	3.4 × 10^2

* Indicates maximum probable temperature at base of Martian exosphere (temperature at which total Mars nitrogen, in g cm^{-2} ≈ total terrestrial nitrogen, in g cm^{-2}).

ture range is 1.5×10^8 to 2.9×10^6 years, and the amount of oxygen which has escaped, plus the amount used in oxidizing iron, lies between 60 and 470 g/cm^{-2}. As shown in Table III, the total amount of water on Mars throughout its history was less than one six-hundredth of the water now present on the earth, provided the equilibrium oxygen content of the Martian atmosphere is 0.35 g cm^{-2}.

From the above considerations it seems likely that Mars never had more than a very shallow ocean. It is not difficult to believe that this is so, because large quantities of water have never seeped out of the planet's interior. This in turn may be related to the apparent absence of mountains and volcanoes. Mars may never have had the turmoil within its interior that has characterized the earth throughout its lifetime. Conversely, it does not appear illogical that the great volume of the terrestrial ocean is a direct result of the continuing turmoil within the earth.

It is possible, as suggested by Urey (1952: 149–157), that the earth's primitive atmosphere contained large amounts of water, ammonia and methane. In the absence of free oxygen, a cold trap might not exist, and moreover ultraviolet radiation could have penetrated to near the ground. Then the initial atmospheric methane would have become oxidized to carbon dioxide within a few hundred million years as a result of the photochemical dissociation of methane and water and the escape of hydrogen. (At the same time the ammonia would have become oxidized to free nitrogen.) If this initial methane corresponded in amount to the total CO_2 present in oceans, atmosphere and sediments, intense chemical weathering should have occurred and vast amounts of sediments, including carbonates particularly, should have been deposited in the very early stages of the earth's history. This does not seem to be consistent with geologic evidence.

Methane may not have been present originally in appreciable quantity but may have come slowly to the surface, but we must then explain why present volcanic gases contain CO_2 and CO and not methane. If the methane did not come in as rapidly as hydrogen escaped, conditions should soon have become oxidizing and a cold trap should have arisen. The rate of flow of water through the cold trap required to produce all the CO_2 by oxidation of methane is 10 times greater than that computed by Kuiper.

It is possible that the methane appeared rapidly enough in the early stages of the earth's history so that conditions remained reducing for a long period and under those conditions no free oxygen and no cold trap existed. During later geologic time the rate of outflow decreased to the point where free oxygen could appear. This would imply that nearly all carbon dioxide now present in the atmosphere, ocean, and sedimentary rocks was produced during early geologic time. Of course, we cannot invoke the hypothesis of photosynthetic production of oxygen and burial of reduced carbon in the form of organic matter in marine sediments to account for production of carbon dioxide and free oxygen from methane and water.

In attempting to resolve this question we may look again with profit to our sister planets Mars and Venus. Urey (1952: 148–150) has suggested that the high concentration of CO_2 and the absence of water in the atmosphere of Venus are due to the photochemical dissociation of methane and water and the resulting oxidation of carbon. But both water and methane are now virtually absent on Venus. Urey's hypothesis would explain this observation if: (1) the amounts of water and methane originally present were just sufficient to balance each other, a coincidence that appears quite unlikely when we remember that both water and methane are also scarce on Mars; or (2) there was an excess of methane, which decomposed to carbon and perhaps refractory carbon compounds. Urey (personal communication) has pointed out that the light yellow color of the Venus cloud layer would appear to rule out the presence of finely divided carbon, which should give a dark "smoky" color.

As several writers have emphasized, the existence of reducing conditions during early stages of the earth's history may have been an essential prerequisite for the origin of life on our planet. The complex organic molecules that are the building blocks of living creatures probably could not have evolved in an oxidizing environment. Thode and his coworkers (Szabo, *et al.*, 1950), from studies of sulphur isotope ratios in sulphides and sulphates of different geologic ages, have suggested that free oxygen did not exist in large amounts until perhaps 800 million years ago. If this were correct, then we might have a satisfactory explanation for the absence of animal fossils in pre-Cambrian rocks and an explanation also for the sudden appearance of fossil remains in many diverse, highly developed animal forms in the Cambrian.

With the growth of biochemical knowledge, the extreme chemical complexity of living things is becoming ever more apparent (see, for example, Wald, 1954). Nearly all this complexity is possessed by even the simplest organisms. It may be that by far the most difficult and time-consuming part of the evolutionary process was the development of the chemistry of the single cell, the building block of all living creatures. This development, including the processes of fermentation, then photosynthesis, and finally respiration could have been carried out entirely by plantlike organisms, which, unlike animals, require no external source of oxygen for their metabolic processes.

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Given the essential chemistry for the organization of living cells, the evolution of animals represents little more than mutations required for the development of a complex morphology, and conceivably they might have happened within a few hundred million years. If we remember that precipitation of calcium carbonate, though easy for plants, which raise the pH by removing carbon dioxide, is a most difficult process for animals, whose principal metabolic products are acid, then it seems likely that the first animals had no hard parts. Considerable diversity of form might have arisen before animals learned how to manufacture shells or skeletons. But once this process was learned, its advantages would be so overwhelming that few animals could survive for long without hard parts.

Thus the sudden appearance of animal fossils in the Cambrian strongly suggests that appreciable amounts of free oxygen did not exist more than a few hundred million years before that time. How, then, can we reconcile the need for reducing conditions in relatively late geologic time with the difficulties previously discussed concerning methane? I believe the answer has been given by Rubey (1951). He has reminded us that volcanic gases contain both CO_2 and CO and has suggested that the organic carbon in the sedimentary rocks can be balanced against the oxygen in the atmosphere, in sulphates and in ferric oxide, provided that approximately a third of the total carbon came to the earth's surface as CO and two-thirds as CO_2. During the early stages of the earth's history, the existence of CO in the atmosphere and oceans would have assured reducing conditions, at least in some parts of the oceans and at times elsewhere. Free oxygen would appear in significant quantities only after the process of photosynthesis had been developed and after sufficient reduced carbon as organic matter had been buried in marine sedimentary rocks.

The reader may well have noted that comparisons of the three terrestrial planets given in preceding pages raise several unanswered questions. For example, why was there more nitrogen than water on Mars and less on the earth? Why is there virtually no water or carbon monoxide on Venus?

It is interesting in this connection to note that the scarcity of oxygen on Mars may be partly an oceanographic phenomenon in reverse. Mars has no oceans, and therefore there is no possibility for the formation of marine sediments with their contained organic remains. Thus, if primitive plants exist on Mars, as seems probable, the oxygen produced by their photosynthesis is used up again by respiration so that none accumulates.

According to Rubey (1951), the geologic evidence indicates that the concentration of CO_2 in the atmosphere and ocean has always been approximately the same as that now existing. From this he concludes that the rate of outflow of volatiles from the earth's interior has been relatively constant. But in the presence of water, the Urey equilibrium would insure a relatively low concentration of atmospheric and oceanic carbon dioxide at all times regardless of the rate of outflow from the interior. At times of more rapid outflow the rates of chemical weathering and of deposition of limestones and other sediments would be increased; at times of slow outflow the rates of weathering and deposition would be slow, other things being equal.

There is some evidence that a considerable portion, perhaps as much as a fourth of all the water in the oceans, has appeared since the late Mesozoic, that is, in the last thirtieth or fortieth of geologic time. Throughout a large area within the "andesite line" in the Pacific Ocean, the presence of coral atolls and flat-topped sea mounts indicates subsidence of the sea floor relative to sea level. This subsidence may have been regional in character, and if so, the approximate constancy of sea level relative to the continental surfaces would require an increase in the total volume of sea water. There is good evidence that, if the subsidence did occur, it took place during the last 100 million years. The fossils found in the drill holes on Bikini and Eniwetok by Ladd and his coworkers (Emery, *et al.*, 1954) are at all depths those of shallow-water, mostly lagoon-dwelling, organisms. At 2500 feet on Bikini, these were early Miocene or late Oligocene in age; at 4500 feet on Eniwetok the fossils were Eocene. Remains of reef corals, echinoids and shallow-water mollusks, dredged from the flat-topped summits of the submerged mid-Pacific mountains between Hawaii and Wake Islands, have been identified by Hamilton (1953) as Middle Cretaceous in age. These summits now lie at depths of 5000 to 6000 feet.

Evidence for a marked increase in the rate of outflow of volatiles may be found also in the character and rate of deposition of deep sea sediments. At the present time, nearly half the deep sea floor is covered with sediments high in calcium carbonate, such as globigerina ooze. These are being deposited at rates of the order of 0.1 to 1 g Ca/m^2/1000 years (Kuenen, 1950). If this rate of deposition has prevailed since the late Mesozoic, that is, since the rise of the pelagic foraminifera, then about a fourth of all limestones now on the earth's surface has been laid down during the last 100 million years. Prior to that time, the deep sea sediments must have been low in calcium. Otherwise, it would be impossible to arrive at a geochemical balance, because both deep-sea and continental sediments would be higher in calcium than the igneous rocks from which they were derived. Because of this change, Kuenen (1950) has suggested that, with the

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rise of pelagic foraminifera, the rate of deposition of calcium carbonate on the deep sea floor has been increased at the expense of the shallow water areas. He supposes that a gradual shift in the location of the sedimentary calcium on the earth is occurring; limestones on the continental platforms are being eroded, and calcium carbonate is accumulating on the deep sea floor, where it will be lost from the calcium cycle. But an alternative explanation is possible: that during late geologic time there has been a great increase in the rate of outflow of carbon dioxide from the earth's interior, with a corresponding increase in the rate of chemical erosion of rocks other than carbonates and in the rate of sediment deposition. The increase in carbon dioxide should have been accompanied also by a corresponding increase in water and other volatiles. The increased supply of calcium from erosion may have stimulated the development of the pelagic foraminifera.

That great events took place in the sea floor in the not distant geologic past is strongly suggested by the extreme thinness of deep sea sediments, as found in both the Atlantic and Pacific by seismic refraction methods. Over a large area in the Pacific, Raitt (Capricorn, 1953) has found that these sediments (at least in unconsolidated form) are only 100 or 200 m thick. A far greater thickness of deep sea sediments is called for by geochemical considerations. The earlier deep sea sediments may have been buried or consolidated in extensive lava flows or other volcanic extrusions that blanketed the sea floor, perhaps during the Mesozoic. Such vast-scale vulcanism should have been accompanied and succeeded by an outpouring of volatiles that may have persisted to the present time.

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STATISTICAL HYDRODYNAMICS[1]

By

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There are two major problems in the theory of hydrodynamics. One is its nonlinear equations. If a fluid motion is specified by giving its velocity at every point, one may inquire whether there is a second possible motion in which the fluid everywhere has just twice the previous velocity. The answer given by theory is "No." While this is simple, it is a negative result, and the problem requires a positive solution. The second problem arises because the observed motions of fluids are often highly irregular and random, typified perhaps by the gusts of wind that follow each other at irregular intervals or by the irregularity of successive breakers.

Many years ago, Osborne Reynolds (1884, 1896) attempted to make progress on both problems at once, and, in a famous investigation that involved both theory and experiment, he founded what has come to be known as the theory of turbulence. His ideas and methods have been fruitful, especially in the work of von Kármán and his followers (von Kármán and Howarth, 1938). However, the results obtained in this way have their limitations. For example, a result obtained in wind-tunnel experiments may be useful in the design of airplanes but may fail to be of much help to the meteorologist or oceanographer.

There is an increasing tendency to depart from Reynolds' path and to attack the two problems separately. The problem of nonlinearity dominates the recent attempts at forecasting weather numerically. While the results obtained are promising, they also indicate the difficult nature of the nonlinear differential equations. Much publicity has been given the high-speed computing machines that can perform millions of additions in a few seconds. When such machines are employed to forecast the motion of air masses over the eastern United States, their capacities are almost reached. And in these calculations, only some of the nonlinear effects are included while the effects of randomness are omitted completely. One says,

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[1] Contribution from Scripps Institution of Oceanography, New Series No. 745a.

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therefore, that turbulence is ignored in these calculations. This appears to be justifiable if one wishes only to forecast the movement of major air-masses 24 or 48 hours in advance.

There are other problems in which the reverse appears to be true. For example, the theory of surface waves indicates that nonlinear effects are subordinate. Two waves, one twice the height of the other, move with almost the same phase speed. This is not exactly true, but within the range of wave-heights encountered at sea, it is a good approximation. But it requires only a glance at the actual sea to be convinced of the randomness of the size, shape, and motion of surface waves.

Thus, an approach to these problems is indicated from the opposite direction: to neglect nonlinearity and concentrate on randomness. G. I. Taylor (1922) laid the foundations for such studies more than 30 years ago. At the present time, his ideas are strongly influencing the experimental attack on these problems. The term "autocorrelation methods" is probably familiar to many of you. These methods are now applied to analyses of wind-tunnel data obtained with the hot-wire anemometer. H. Panofsky is using them to analyse the natural wind. Here at Woods Hole, Seiwell applied them to ocean waves, and P. Rudnick has done the same at the Marine Physical Laboratory.

It is the theoretical rather than the empirical aspect of this approach that I wish to emphasize today. One can easily distinguish two very general kinds of random motion. The one is typified by the vertical motion of the sea surface over a point whose horizontal co-ordinates are fixed. The elevation changes, but its mean value is zero, being sometimes higher and sometimes lower. One may call this kind of motion a random oscillation—the variable oscillates about its mean value, but in a highly irregular manner.

The other type of motion can be illustrated by considering a small boat adrift at sea. If it is in the region of a steady wind, it will move down wind, and, on the average, it will move by equal amounts on successive days. But if it is in a region of light and variable winds, with no steady ocean currents, it will not show such a steady motion in one direction. Neither will it tend to return to its original position. It can be shown that its distance from the starting point increases (on the average) as the square root of the time but that it has no predictable direction. One may call this a random drift. In his highly original paper on such matters, G. I. Taylor used the phrase "diffusion by continuous motion" to refer to this phenomenon when applied to masses of fluid.

The theory of molecular diffusion had also encountered a similar thing. This theory is based on the idea that in general the molecules of a gas move in straight lines with constant speed. This motion is altered abruptly by collisions with other molecules. Thus, the path of a given molecule consists of segments of straight lines, of random lengths and directions. In this case also, the distance from the starting point increases (on the average) as the square root of the time. The motion differs from the random drift in its segmental, discontinuous character: it has variously been called a random walk, or a random flight.

The distinction between the random drift and the random flight appears to be quite important, although not all problems are solved. In the kinetic theory of gases, it is shown that the random flights of molecules can be described by the so-called diffusion equation. It has often been supposed that this equation will also describe the random drift of water masses, and this has led to the well known concepts of coefficients of eddy-diffusion, mixing lengths, etc. Unfortunately, these concepts have, empirically, been unsuccessful in describing the motion of water masses in a quantitatively precise manner. At most, the diffusion equation can be supposed to yield a qualitative impression of the actual phenomena.

If one examines the theoretical derivations of the diffusion equation, one finds that they are all based on random flights of well defined objects. A water mass is not a well defined object and its motion is not a random flight in the sense of the above discussion. Moreover, it is difficult to modify the usual derivations of the diffusion equation so that they apply to this more general kind of random motion. One may therefore conclude that the failure to confirm the diffusion equation when applied to water masses is not a failure of the theory.[2] But this again is a negative result.

In order to describe the more positive results, I shall have to go into more detail. Norbert Wiener's (1949) great contribution to the subject has shown that a random oscillation always has a continuous power spectrum—and conversely. In one way, this is an old result, familiar from the wave theory of white light. This, long considered to be a random oscillation, is known to have a continuous spectrum. However, Wiener's analysis opens the way to many new calculations and to a discussion of random drifts.

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[2] In the discussion at the Convocation, Professor E. Bright Wilson called attention to unsolved problems in this connection. Perhaps his remarks may be paraphrased as follows: the molecules of a gas execute random flights, but those of a liquid execute random drifts, since they are never free of the force fields due to neighboring molecules. Consequently, if the views advanced above are correct, one would expect the diffusion equation to be verified for gases, not for liquids. But, empirically, it is found to be equally applicable to both. This would lead one to expect that the diffusion equation would also govern the random drift of water masses, unless it can be shown that these are basically different from the molecules of a liquid. One such difference is their lack of permanent individuality.

Let $x(t)$ be the co-ordinate of a point that executes a random oscillation. To this function, $x(t)$, there is associated a spectrum function $S_x(\omega)$, where ω is the frequency. This association is such that the area of the $S_x(\omega)$ graph is the time average of x^2, or, if one wishes, the square of the amplitude of the random oscillation. Now let

$$u(t) = (dx/dt)$$

be the velocity of the point; there will also be a spectrum function, $S_u(\omega)$, associated to $u(t)$; since the velocity will also oscillate randomly, this is given by the equation

$$S_u(\omega) = \omega^2 S_x(\omega).$$

The relation between S_x and S_u is shown in Fig. 1. It is important to notice that $S_u(\omega)$ approaches zero with a horizontal tangent, as ω approaches zero.

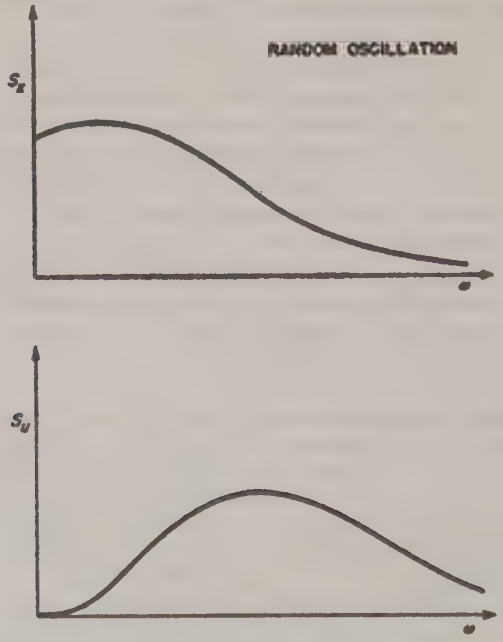

Figure 1. Relation between displacement and velocity spectra for a random oscillation.

Thus far I have been speaking of a random oscillation. Let me now turn to the random drift. In this case, the velocity still oscillates randomly, but $S_u(\omega)$ may not approach zero, or if it does, it may not do so with a horizontal tangent. If we now calculate

$$S_x(\omega) = S_u(\omega)/\omega^2,$$

we find that $S_x(0) = \infty$. The area under the $S_x(\omega)$ graph will then be infinite (see Fig. 2) and the amplitude of the displacement will diverge. This is precisely the characteristic of a random drift.

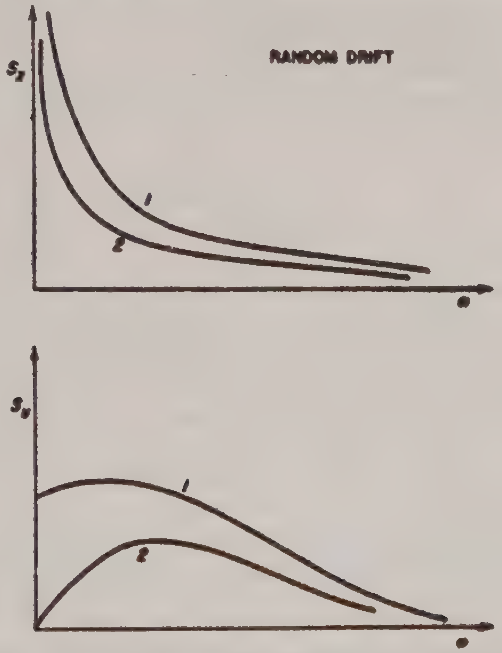

Figure 2. Relation between displacement and velocity spectra for random drifts.

We have thus learned to distinguish between random oscillations and random drifts by an inspection of the velocity spectrum. We see that the distinction depends on the low frequency components in the variation of the velocity and that these must be very small indeed if the motion is to be random oscillation.

Now, if one neglects the nonlinear effects, it is possible to make many calculations about random oscillations and random drifts. This becomes almost as easy as the corresponding calculations about simple harmonic oscillations. I shall summarize the results of three such calculations.

In each, it was postulated that the vertical displacement of the sea surface is a random oscillation, not a random drift. In each, the objective was to see if the horizontal motion could then be a random drift.

In the first calculation it was supposed that the ocean had infinite depth and was incompressible—had the same density at all depths. The usual approximations of the linearized theory of gravity waves were introduced. It was then found that the horizontal motions were everywhere random oscillations. It was impossible for horizontal random drifts to occur unless the sea surface was so violently agitated that the rms wave-height was infinite.

In the second calculation, the ocean depth was supposed to be finite, whereas all other approximations were retained. It was then found that horizontal random drifts were possible and obeyed the law

$$X = KZ\sqrt{(T/D)}.$$

Here

Z = rms height of the gravity waves,
X = rms horizontal displacement occurring in the time interval T,
D = depth of ocean,
K = factor depending on depth below surface at which X is determined, etc., etc.

From this one would conclude that random drifts should be more pronounced in shallow water than in deep, and this is probably in accord with the facts. This was not all that could be determined: One could consider the relative motion of two nearby particles of water and show that this must be a random oscillation. The two particles might drift, relatively to the bottom, but they could not drift apart.

In the third calculation, the water was supposed to be stably stratified, its density increasing exponentially with depth. It was therefore possible for internal waves to occur, in addition to the surface gravity waves. The latter caused horizontal random drifts governed by the same formula as that given above. The internal waves, however, caused random drifts governed by the formula

$$X_I = K_I\,(Z_I/D)\,\sqrt{T}\quad,$$

Z_I being the amplitude of the internal waves. The dependence on T—the time interval required for the rms displacement X_I —is the same, but the ocean depth enters in a different way. Moreover, if one now considers two particles, they may drift apart. This is so essentially because a stratified ocean has many modes of oscillation

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while an ocean of constant density can oscillate only with surface waves.

These calculations have therefore isolated two factors that together can cause the random drift of water masses: the one is the bottom, the other is the density gradient. Neither, by itself, can cause drift.

I do not think that this is the only mechanism that causes the random drift of water masses in the ocean, but it is an especially simple one. Another mechanism is undoubtedly connected with steady currents, which, by themselves, would cause only steady displacements, increasing linearly with time. When these are combined with surface and internal waves, a random drift may be superposed on the steady displacement. The necessary calculations for this problem are not impossibly difficult, but so far they have not been completed.

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HIGH FREQUENCY SPECTRUM OF OCEAN WAVES[1]

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The subject "Motion in the Ocean," assigned to me by President Bronk, includes fish, Aqua-lung divers and density flows. For a very good reason I must confine myself to motion of the water itself. Further, I will limit myself by considering only that part of the motion of ocean water that can be associated with surface waves. It is nearly, but not quite, the irrotational component of the motion. This of course limits the subject, but not so much as you may think. It is by no means impossible that some processes previously explained by turbulence—the oceanographer's way of saying that he doesn't understand—are part of the surface wave problem[2] and that the Gulf Stream would be only a fraction of its present magnitude if the high frequency tail of the surface wave spectrum, the wavelets and the capillaries, were to be wiped out by an oceanwide slick resulting from a diatom bloom of impossible proportions.

The evidence for the latter statement was an experiment performed by Keulegan in a closed flume and repeated by Van Dorn in a 200 m long model-yacht basin. If TIDE, SURF, or some other detergent with a suitable oceanographic name, is sprinkled on a water surface over which a wind is blowing, the capillaries are quickly damped. This in turn has two effects: (1) The momentum transfer from wind to water (stress) is significantly reduced at all but low winds, and (2) the larger waves present, though not directly affected by the detergent, fail to be regenerated.

Apparently the tiny waves play a disproportionately important rôle in the problem of wind stress as well as in the generation of the more prominent parts of the wave spectrum. This was the beginning of a three year study.

The Spectrum. Let me first review what we mean by spectrum. Suppose we record against time the elevation of the sea surface above

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[1] Contribution from the Scripps Institution of Oceanography, New Series No. 745b. being a report on progress in studies supported under a contract with the Air Force Cambridge Research Center.

[2] See Carl Eckart, Statistical Hydrodynamics, in this issue.

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mean sea level, $z(t)$. If we use a tide gauge, we automatically discriminate against waves and swell in favor of the longer period (lower frequency) oscillation of tides. With a standard wave recorder we record waves and swell, but the instrument is rather unresponsive to capillaries, and perhaps to tides as well. Each instrument has its working range of frequency. Consider now an ideal instrument which is tuned with equal sensitivity to some narrow band of frequencies, from $f_0 - \frac{1}{2}\,\delta f$ to $f_0 + \frac{1}{2}\,\delta f$, but which does not respond at all to frequencies outside of this band. We now record the elevation of the sea surface (relative to mean sea level) through this spectral window. This gives us a wiggly record $z_{f_0}(t)$. The mean value of z_{f_0} is zero and is not interesting. The mean value of $(z_{f_0})^2$ is not zero and is interesting. It will be designated as $S(f_0)\,\delta f$, where $S(f_0)$ is the spectral density of the surface elevation (or simply, the spectrum) for the particular central frequency, f_0, to which our instrument was tuned. We now tune to a different frequency, f_1, and get a value of $S(f_1)$; by tuning to many such frequencies we generate the entire spectrum.

For our purposes it is more convenient to consider the spectrum $S(k)$ generated by an instrument tuned to a certain limited band of wave numbers k, where $k = 2\pi/\text{wave length}$. For example, the pitching motion of a ship is responsive to neither capillaries nor tides but only to wave lengths of the general order of the length of the ship. In actual practice the best way of determining $S(k)$ is to measure $S(f)$ and to make a theoretical transform. As a result of the work by Pierson and Neumann at New York University we have a fairly good idea of what $S(k)$ looks like (Fig. 1). It is peaked near

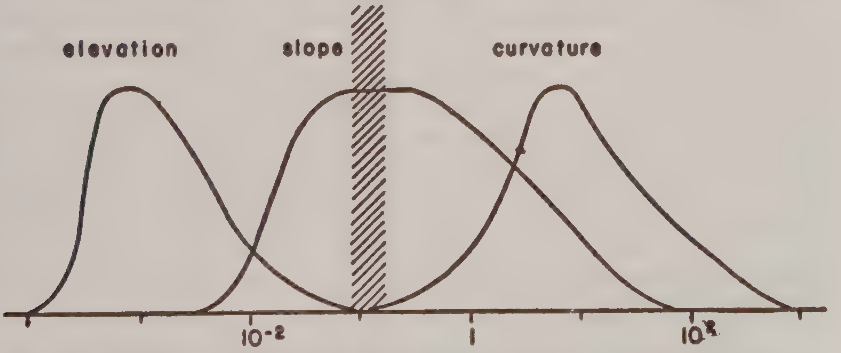

Figure 1. Schematic presentation of the spectra of elevation, slope and curvature as a function of the wave number k (units cm^{-1}). A slick has the effect of dissipating the parts of the spectra lying to the right of the vertical band.

$k = 5 \times 10^{-4}$ cm^{-1}, meaning that wave lengths of $2\pi/5 \times 10^{-4}$ cm, or about 100 m, contribute most to the spectrum. The contributions from waves longer than 500 m and shorter than 1 m are negligible. The total area under the curve is the contribution to the mean value of $z^2(t)$ from waves of all lengths, in other words, the mean square elevation, $\overline{z^2}$. The square root of this value, the rms elevation, comes close to what an observer would estimate to be the amplitude of the waves.

The two other curves in Fig. 1 are the spectra of slope and of curvature. The interpretation is as before. All we need to do is insert the word "slope" or "curvature" in the place of "elevation." It can be shown that the three spectra are given by

$$S(k), \qquad k^2S(k), \qquad k^4S(k), \tag{1}$$

respectively. Hence they are progressively weighted in favor of larger k's (i.e., short wave lengths, short periods, high frequencies) so that the study of slope and curvature provides a tool for learning about the high frequencies. The areas under the three curves are then interpreted as follows:

$$\begin{aligned} &\text{mean square elevation:} && \int_0^\infty S(k)\,dk, \\ &\text{mean square slope:} && \int_0^\infty k^2S(k)\,dk, \qquad (2) \\ &\text{mean square curvature:} && \int_0^\infty k^4S(k)\,dk. \end{aligned}$$

These three integrals likewise provide a means of studying the spectrum with an increasing emphasis on high frequency. They are, in fact, the zero, second and fourth moments of $S(k)$, and if all moments were known, $S(k)$ itself could be reconstructed.

The procedure we have followed is to measure the mean square slope, and some work on curvature is now underway. The mean square values are easier to measure than their spectra. One needs only to record elevation (or slope, or curvature) by means of an instrument whose response is reasonably "flat" over the important range of the spectrum, square the output, and average. I shall now describe some measurements and what they have taught us about the high frequencies.

Sun Glitter. In the late summer of 1951, Charles Cox and I flew to the island of Maui, T. H., in a B-17 research plane provided by the Air Force as part of our Air-Sea Boundary contract. Gifford

Ewing's 58′ schooner, the REVERIE, went out under sail to make the necessary surface measurements, particularly of wind speed and direction. The principal goal was to measure mean square slope from photographs of sun glitter. The idea is simple. If the sea surface were flat calm, the glitter would be small; in fact, it would consist of a single undistorted image of the sun itself. But when the water is roughened there are thousands of dancing highlights within an extended glitter pattern. Each is a tiny image of the sun due to a reflection of a ray from an appropriately inclined water facet. The principle is quite old, having in fact been mentioned by Spooner in 1822 in *Correspondence with Baron de Zach.*

We have related the statistics of the slopes to the distribution of radiance in the glitter area. Our results, which I believe are more quantitative than those previously obtained, have been reported in a paper in which Cox is senior author.[3] Let me review the results briefly.

Distribution of Slopes. One result concerns directionality. It is possible to build up the mean square slope from contributions by waves of all possible directions, just as we had previously considered contributions by waves of different frequencies. When this is done it is found that, of those relatively short waves that are prominent in the slope spectrum, a substantial portion travels up to 60° to either side of the wind. This is a surprisingly wide beam into which the winds generate waves, a fact that must be taken into account in any theory of wave generation. The corresponding beam of the elevation spectrum, which features the longer waves, appears to be a bit narrower.

The slope distribution itself is nearly Gaussian, and, as is to be expected, the mean square values increase with wind speed. For a wind speed of 14 m sec^{-1} the rms slope is tan 16°. This means that there is a 10% chance that the slope exceeds 22° and a 1% chance that it exceeds 30°.

Since the distribution is nearly Gaussian, it can be represented by a single number, such as its mean square value. Cox and I found that the mean square slope increases *linearly* with wind speed. Now, if the elevation spectrum $S(k)$ is known, the mean square slope, $\int_0^\infty k^2 S(k)\, dk$, can be derived theoretically. Gerhard Neumann has proposed a particular form of an elevation spectrum which involves the wind speed as a parameter, and we find that it yields just such a linear relation as we have observed. This is a satisfying result. It means that Neumann's lengthy observation of wave heights from the bridge of a German freighter plowing the Atlantic and our photographs of the sun's glitter in the Alenuihaha Channel yield consistent results. If I seem overjoyed by a consistency that is no different from that which should be expected and which is in fact found in other fields of physics, it is because most oceanographers have not been spoiled in this regard.

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[3] Cox, Charles and W. H. Munk, 1954, statistics of the sea surface derived from sun glitter, J. Mar. Res., *13* (2): 198–227.

The linear relation is only part of the story. What about the proportionality constant? Here it is found that the rms slopes computed from Neumann's spectrum equal 60% of the values we observed. There are two ways of remedying the discrepancy, but I am not sure whether either of them, or the discrepancy itself, is significant. One is to fit Darbyshire's recorded data,[4] which are in some aspects superior to Neumann's observations, to Neumann's spectral function. The other is to compare Neumann's original coefficient with our observations in the presence of slicks.

The last remark needs some amplification. One of the duties of the Reverie was to pump a mixture of diesel oil, used crankcase oil and sardine oil onto the water to make a coherent slick about one-quarter square mile in area. It was found that the mean square slope was reduced in this way by a factor of two or three, apparently by the elimination from the spectrum of waves shorter than a foot (Fig. 1). We have considered at some length why this should be so. We know, by the amount of oil added and by the presence of interference colors, that the slick was perhaps 1000 molecules thick. Reynolds' classical theory for monomolecular layers does not apply. The reason for the damping remains obscure, but the question *whether* oil dampens waves can be answered in a fashion. By removing only the high frequency components, the mean square elevation is nearly unaffected, the mean square slope is reduced by a factor of two or three, and the mean square curvature is virtually eliminated. The optical properties of the surface are greatly altered, giving the appearance of smoothness seen otherwise on calm days only. I wonder whether this is not part of the reason why oil has been poured on troubled waters since time immemorial.

Curvature. The success achieved by the Neumann spectrum in predicting the distribution of slopes provides a temptation to extend it even further to inquire what it has to say about curvature. In doing so we realize that this means extending it far beyond the range intended by the author.

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[4] Darbyshire's own fit, defective in the high frequencies, yields a *decrease* in mean square slope with increasing wind speed. It has been suggested by Deacon at the UGGI meeting in Rome that the discrepancy may be due in part to generation in shallow water.

The Neumann spectrum predicts a mean square curvature which corresponds to a 12 cm radius of curvature and which is nearly independent of wind speed. Cox is now making measurements of curvature by sweeping a photomultiplier tube across a small area of sea surface and counting glitters. It can be demonstrated that the values so obtained can be used to compute the statistics of curvature. It is really too early to be certain, but it now appears as if the Neumann curvature is too low and that curvature does increase with increasing wind speed. Thus it may turn out that the Neumann spectrum is deficient in the capillaries and that we may find here a separate band of high activity.

It should be mentioned that the group velocity of waves reaches a minimum value of 17.8 cm sec^{-1} for a wave length of 4.4 cm. The minimum represents a balance, so to say, between surface tension and gravity. Shorter waves are principally affected by surface tension, longer waves by gravity. It is not unusual in geophysical problems to find prominent features in records to be associated with such a minimum in group velocity.

Dissipation. Another feature may make the study of slope and curvature rewarding. It can be shown that the energy dissipated due to molecular viscosity by wave numbers in the range $k \pm \frac{1}{2}\,\delta k$ equals

$$4\mu g\, k^2\, S(k)\, \delta k + 4\mu\gamma\, k^4\, S(k)\, \delta k \quad , \tag{3}$$

where μ is the molecular viscosity and γ the specific surface tension. Comparison with (1) shows that the two terms are proportional to the slope and curvature spectra, respectively. The total dissipation, due to all wave numbers, is therefore

$$4\mu g\sigma^2 + 4\mu\gamma\kappa^2 \quad ,$$

where σ^2 and κ^2 are mean square slope and curvature (eq. 2).

For a 10 m sec^{-1} wind we find $\sigma^2 = .06$. Blowing wind over Washington tap water, Schooley found $\kappa^2 = 1\ \text{cm}^{-2}$. With these values, each of the two above terms equals approximately 2.5 ergs $\text{cm}^{-2}\text{sec}^{-1}$. If it should turn out that there is a separate band of high activity in the capillaries, then the second term would be correspondingly larger.

We have here an optical method for studying an energy sink of the ocean wave spectrum. Perhaps the energy is passed on by some nonlinear process (white-capping?) from the longer to the shorter waves until it is finally dissipated by the high-frequency components. This would be analogous to conditions as found in the turbulence spectrum. The point of view is opposite to the one taken at the start of this discussion, when we pointed out that the growth of the larger waves requires the existence of the very short ones. Could it be that the capillaries provide for both construction and destruction of ordinary waves?

It should be pointed out that dissipation by capillaries is not the only way in which wave energy can ultimately be dissipated. Surface wave energy may also go directly into turbulent energy, by breaking or otherwise, and be dissipated finally by the small elements of the turbulence spectrum. Perhaps one can gain some insight into this aspect of dissipation by the following approach. It was pointed out to me by Norman Barber that the statistics of *acceleration* are closely related to the statistics of slope. Thus, for a wave profile $z = A \cos (kx - \omega t)$, the slope $\partial z/\partial x$ has an amplitude kA, the vertical acceleration $\partial^2 z/\partial t^2$ has an amplitude $\omega^2 A$, and, for the linear theory, $\omega^2 = gk$. Thus the accelerations at the surface, measured in units of g, equal the tilt in radians. For a 14 m $\sec^{-1}$ wind we found an rms slope of tan 16°; accordingly the rms acceleration is about $\frac{1}{4}\ g$. There is a 1% chance that it exceeds $\frac{1}{2}\ g$. If one dares to extrapolate this distribution even further, one can compute the probability that the acceleration exceeds g. Spray would certainly be formed if the acceleration exceeded g. There are obvious difficulties with this approach, but in some ways I find it more attractive than a discussion based on conventional breakers with 120° cusps. As an aside, what is the effect on micro-organisms near the ocean's surface when they are being tossed around with an rms acceleration of $\frac{1}{4}\ g$?

Wind Stress. We now return briefly to a problem mentioned at the beginning of this paper, namely the transfer of momentum from wind to water. At the Rome meeting of UGGI, Charnock gave a critical summary of reliable observations and concluded that this transfer increased with wind speed U faster than U^2 but slower than U^3. I think our results are not inconsistent with this conclusion.

If spray and rain can be neglected, the transfer of momentum is accomplished by two processes. First there is a transfer by *skin drag* as it is found whenever fluid flows over polished plates. It equals $\mu\ (dv/dz)_{z=0}$ either in the water or the air, with the shear dv/dz evaluated at the very surface. There have been no systematic attempts to measure dv/dz close to the surface. I am impressed with a casual observation by Kittredge. Working from a skiff, he put some dye on the water and then sprinkled a bit of talcum on the dye. He found that the talcum drifted apart from the dye mark at a rate of something like 10 cm sec^{-1}. If we set the thickness of the dye as 1 mm, then the shear must have been of the order

$$\frac{10 \text{ cm sec}^{-1}}{0.1 \text{ cm}} = 100 \text{ sec}^{-1} ,$$

and μ times this quantity equals 1 dyne cm^{-2}. This is of the expected magnitude for the shear stress.

In analogy with other experimental evidence one can expect the skin friction to be proportional to U^2. In addition there is a transfer due to *form drag* resulting from systematic differences in pressure on the windward and lee sides of waves. Air impinging onto a vertical surface exerts a pressure ρU^2. If the slope is zero, the pressure is zero. The simplest interpolation between these values is then $\rho U^2 m$, where $m = \sin \theta$ and θ is the tilt in the direction of the wind. So far this is equivalent to Jeffreys' sheltering theory. The horizontal component of this pressure is $\rho U^2 m^2$. If the tilted surfaces move downwind with a velocity C, the appropriate expression is $\rho\ (U - C)^2\ m^2$. Over land, $C = O$ and m^2 is constant. The form drag accordingly varies as U^2. Over water, if $C \ll U$, then the average value of the above expression is $\rho\ U^2 <m^2>$, where $<m^2>$ is the mean square slope component. Our results show that $<m^2>$ increases linearly with U, and hence the form drag varies as U^3. To allow for C, one is tempted to write the above expression in the spectral form

$$\rho \int_0^\infty [U - C(k)]^2\, k^2\, S(k)\, dk \ .$$

The integrand represents the contribution to the total form drag by wave numbers in the interval $k \pm \frac{1}{2}\, \delta k$. The integration can be carried out for the Neumann spectrum in closed form. One finds that the drag again varies as U^3 and that the resulting formula can be made to fit Van Dorn's and Charnock's results.

I won't make too much of this circumstance because of the many uncertainties involved. At what elevation is the wind to be measured? What is the effect of the lapse rate? Can the momentum transfer (and pressure pattern) for each wave number be assumed independent of other wave numbers, as implied in the foregoing integral? Can skin drag be added to surface drag? Is $C(k)$ the phase velocity, or does it involve also the orbital velocity of the larger waves present?

But, regardless of these difficulties, I am convinced that the form drag is much more closely related to the slope statistics than to the elevation statistics. I believe this conclusion is a departure from the usually accepted view. There one deals with Reynolds numbers, or with roughness coefficients; and in either case, a length parameter is involved which is supposed to be mysteriously related to wave height. If the elevation statistics were essential, then the effect of a six foot sea on form drag would be equivalent to that of a six foot tide! If this were so, one would expect a critical dependence of wind stress on fetch and no measurable effect due to a detergent spread on the water surface. On the other hand, if the slope statistics, hence the high frequency spectrum, is the essential element of surface roughness, then the dependence of wind stress on fetch should be slight, as observed; and the reduction by a slick should be considerable, again as observed.

Before leaving this subject I should like to bring up one more possibility. The glitter measurements have shown that the wave spectrum is symmetrical with respect to wind direction, as expected. But under special conditions this directional spectrum might be skewed in the sense that waves travelling to the left of the wind would be more prominent than those to the right, or vice versa. This would give rise to a crosswind component in form drag. Henry Stommel has made the interesting suggestion that attenuation of high-frequency waves by slick bands lined up with the wind would result in just such a directional skewness and that this would give a component of drag into the slick from both sides of the slick. There would then be a convergence in flow which might serve to maintain the slick in the compressed state prerequisite to wave attenuation.

Comments on the Statistical Approach. By this time some violent objections to our statistical point of view will have developed in the mind of the listener. If he is a plant taxonomist he is likely to ask where we would stand today if our knowledge of diatoms and their wondrous diversity consisted of statistical descriptions of their geometry. Are we obscuring observable quantities behind statistical curtains? Certainly "mean square slope" and "mean square curvature" are not readily identified with anything we can see on the sea surface. And even if it is admitted that some statistical treatment is required, why choose probability distributions and spectra among the many possible statistical descriptions?

I really don't know of a good answer to these objections, but at least a few things can be said in favor of our choice. Suppose you were to ask me about wave conditions off La Jolla in June and I were to reply by presenting you with file cabinets filled with records of wiggly lines. I don't think this would be quite satisfactory. Apparently some kind of statistical generalizations are in order. But which are the most pertinent? This depends entirely on the problem to be solved, and for a great variety of problems the spectral description is convenient. Pierson and St. Denis have made remarkable progress in studying the motion of ships in a rough sea by first decomposing the sea surface into a spectrum of elementary sine waves of all possible lengths and directions and then considering the response of the ship to each of these. The essence here is that the response of the vessel be *linear*, i.e., that the total response should be the sum of the responses to the individual trains; this is pretty much the case so long as there is no green water over the bow. An example for high frequency waves is the scatter of radar and sound waves from a rough sea surface. This can be estimated from a knowledge of the wave spectrum. The only components of the wave spectrum that are important here are those whose wave lengths are of the same order as the wave lengths of the radar or sound waves. For present equipment this means the high frequency tail of the spectrum.

However, our principal interest is not to compute the scatter of radar waves, even though this is a matter of some importance, but to work toward a respectable theory of the generation and decay of ocean waves and of the transfer of momentum across the air-sea boundary. How does the spectrum help here? In other fields of physics a knowledge of the spectrum has helped a lot in pointing the way toward a successful theory. If at some future time a theory of wave generation should critically confirm the Neumann spectral function, such a theory should be considered a major achievement.

On the other hand, it is certainly dangerous to select one's statistical tools without having first had a good look at observations uncontaminated by analysis. Fig. 2 shows a remarkable photograph taken by von Arx off the Woods Hole dock. In spite of considerable effort I have never been able to improve on this picture. It shows a series of tiny wavelets on the lee side of larger waves, with the shortest wavelet farthest out in front (downwind). On days with light winds, wavelets can be seen by the naked eye. Wavelets are eliminated by a slick, and I suspect, therefore, that they represent a major contribution to the statistics of curvature. However, what may be the essential features of wavelets, their dispersive appearance and their location relative to the crests of the longer waves, could be buried by routine measurements of curvature. To put these features into an appropriate statistical language requires more elaborate statistics. I think this photograph indicates how important it is to look at the raw data before deciding on pertinent statistical parameters.

I have a simple hypothesis as to why these dispersive wavelets are

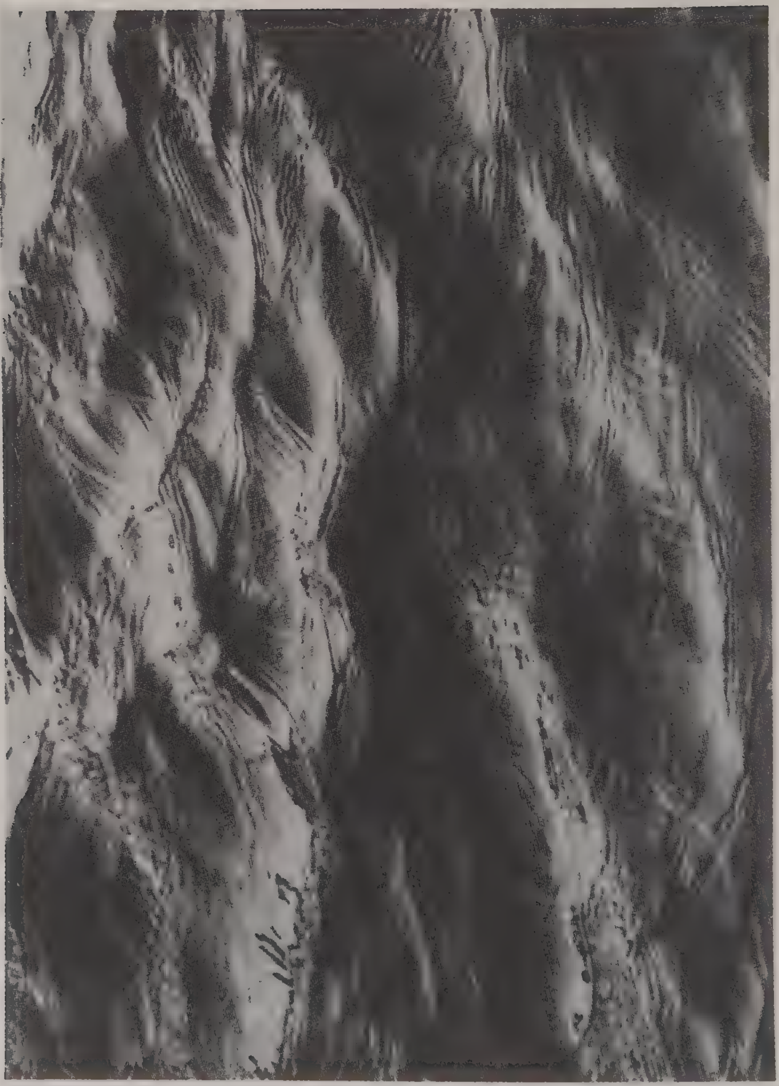

Figure 2. The wind blows from right to left.

found only forward of the wave crest and why the short waves lead the long waves. Consider (Fig. 3) an underlying long-crested wave with height H, phase velocity C, and orbital velocity U (less than C). Capillaries with phase velocity c ride this wave. Their total rate of advance is $c + U$, and they will remain stationary with respect to the wave crests provided

$$C = c + U(x) \; . \tag{4}$$

Consider first the region (1) to (2) forward (to the right) of the crest. If $c + U$ were to exceed C slightly, the capillary would advance to a region of lesser U until eq. (4) is again satisfied. If $c + U$ is slightly less that C, then the capillary falls back toward the crest where the orbital motion is faster, and equilibrium is again achieved. However, in the region (2) to (3) behind the crest, a slight variation from the stationary condition leads to conditions for the permanent removal of the capillary from this region. Stationary conditions exist only forward of the crest, and to the rear of the trough. This is in fact where the capillaries are found.

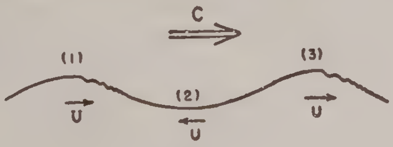

Figure 3.

We now wish to find the capillary wave lengths. The simplest case is one for which $L \gg L_m$ and $l \ll L_m$, where L and l are the lengths of the waves and capillaries, respectively, and where $L_m = 1.7$ cm, the wave length for minimum phase velocity. It can then be shown that

$$l = \frac{L_m^2}{L}\left(1 - \pi \frac{H}{L} \cos \frac{2\pi x}{L}\right)^{-2} ,$$

where x is the distance forward of the crest. Since $H \ll L$, this means that l is largest near the crest, then diminishes forward. Qualitatively this agrees with what is observed.

There is an alternative, and perhaps an even simpler hypothesis. Suppose one takes a straight edge (thin compared to L_m) and brushes it across water at a velocity exceeding the minimum phase velocity (23 cm sec^{-1}). Then one eventually finds a series of capillaries preceding the straight edge and gravity waves following it, with each crest remaining parallel and at a fixed distance from the ruler. The short waves are in front because their energy is propagated faster than the wave crests. The reverse holds for the relatively long waves to the rear. This is the one-dimensional equivalent to the "fish-line problem," and it is fully discussed by Lamb (p. 270–271, 6th ed.).

It is not unreasonable to assume that, at the very crests of waves, where instability first manifests itself, such a travelling stress is applied. If this happens over only a short period, then there will be noticeable dispersion, with the shortest waves farthest in front. In this sense, the capillaries on the photograph may represent a shock front in a dispersive medium.

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OCEANOGRAPHY AND ENGINEERING[1]

By

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I have been greatly honored by the invitation to this gathering and to the dedication of this newest and most impressive implement to the study of the province of oceanography.

I wish that I could unveil some blinding breakthrough to shine by its own light in this assemblage. However, I present only a few humble rays that interrelate two great fields of human effort, Oceanography and Engineering, and the light engendered thereby is scarcely adequate to view their raveling. It seems happily appropriate to me to discuss these relations, virtually within sight of this laboratory which we might consider as being recognition of the value and implications of oceanography to a great branch of engineering, Naval Science. In this discussion I hope to indicate several ways in which Engineering and Oceanography are related and to discuss what I consider the most important mutual problem of these two provinces, the need for rational realistic co-operative attack on complex problems.

Certainly I do not need to point out the many ways in which the information of the oceanographer is of importance to the engineer who is involved in marine problems. Such lack of exchange of information as does exist is being reduced rapidly as the engineer becomes better acquainted with the reality of the oceans and becomes better able to ask questions. Recent work on west coast sewer outfalls is an example. Engineers, troubled by the stability of a surface layer of light effluent from their great outfalls, have, with the aid of oceanographers, planned to effect mixing of the effluent below the thermocline and thereby avoid surface stability. Many such examples could be enumerated. Recognition of the variability of ocean waves in ship-model studies is another valuable step toward realism.

In the application of engineering information and methods to oceanography, the record is not so commendable. Certainly much of the engineering information on models, evaporation, turbulence, settling, jets, and mixing is amenable to generalizations, with immense implication to studies of oceanographic processes. A type of problem

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[1] Contribution from the Scripps Institution of Oceanography, New Series No. 745c.

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that springs to mind is that of the eventual history of the downwardly projected mass of water in a deep-sea comber. Can its momentum be balanced short of the thermocline? Is it important in the deepening and steepening of the thermocline?—in mixing?—in friction? Surely there are many engineering investigations on jet mixing that will increase evaluation of the importance of such possible processes. Woods Hole scientists have employed engineering methods in their important investigations of oceanic circulation. Others, including myself, have applied engineering model laws to such matters as the motion of sea animals, with highly suggestive results. For instance, in studying the model laws of a simple prey-predator relationship, I am convinced that the factors which limit the size of predatory pelagic fishes are demonstrable, that many outstanding characteristics of fish form can be explained, and that probably a strong evolutionary requirement for the development of rapid changes in the schooling habits of pelagic fishes can be demonstrated.

I believe that there is great potential value in exchange of information and methods in this direction and that this should be fostered. However, the fact that one should consider it necessary to suggest a mere exchange between oceanography and engineering points up a far more important and extensive problem in the relationship of the "pure" and "applied" fields. I have felt that here a grave gap exists in our methods of progress toward understanding. To enable me to point out this problem, why it has arisen, and why it is seldom recognized, I will follow, for what they are worth, some contemplations which begin with the hierarchy of man's endeavors to discover the truths of the world.

May we not say that all of man's effort to understand the universe stems from a need to feel more secure within it? I believe that this is so and that the sense of security is of two kinds. The first results from an understanding of "what will something do?" and "what will be something's effects?" Underlying this is the necessity to understand "what is this something like now?" and "how did it get that way?" This is the realm of science, and its "purity" depends inversely upon how far it goes into the crass problem of "how can the effects, particularly on mankind, be altered?"

The sense of security that results from the description of something and from an understanding of the processes which explain its state and its probable future course must consist of a feeling of unity with the environment and must be what we speak of as "spiritual security." Is not the great potential benefit of science to mankind such that men might be relieved from the necessity of explaining physical events by supernatural forces? If so, it is the benefit which has no organized group for its harvesting but which is left as an untouched reward for the worker and some interested gleaners.

The further sense of security results from having altered the effects. This is the province of engineering, which is charged with the imperative statement, "alter the effects of something!" The degree of the "applied" nature of engineering depends inversely upon the degree of its investigations into the questions, "what are the effects of something?" and "what is the something like?" Engineering goes far into these areas, especially where science does not see fit to go. And it does so because the rational approach to its problem of control must be founded on understanding.

Nevertheless, basically science is charged with the problem of "what will something do?" while engineering is charged with "do something about it." The sense of security gained from pure science is a security of the spirit and its reapings are poorly disseminated, while the sense of security gained from engineering is physical and its harvesting is highly organized.

These foregoing statements leave a great area untouched. Originally the "somethings" were natural[2] parts or processes of the universe, but today many of them have already been acted upon by man for their alteration. The sullying effects of man, except for those of the scientists involved, must not exist in the "something" under investigation if science is to be the purest.

This curious idea of the uncleanliness of man's effects on nature, or rather, of man's unnaturalness, has resulted in a great group of studies, intermediate between science and engineering, which science calls applied and which engineering calls basic. These studies are fostered more by engineering than by science, but they suffer from the dichotomy. Surely they are as true a study into the truth as any. Consider metallurgy. A "pure" metallurgy could inquire only into the nature of "native" copper, gold or meteoritic iron. Is there not as much truth in steel as in meteoritic iron insofar as the state of matter is concerned? Yet the metallurgy of steel is relegated to the applied category. Or consider the genetics of *Drosophila* as opposed to horse breeding.

I believe that this attitude and the resultant dichotomy would be entirely defensible had science pursued and organized itself for its most important task to man, the generation of spiritual security through understanding. I cannot see that this has been much considered. One may argue, of course, that the revelation of truth will, in fact, not result in spiritual security. To this speculation there is no answer, for its conditions have not been discovered.

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[2] For later emphasis I leave this word as I first unconsciously used it.

For completeness I must continue the argument around the last radian of its circle.

Concerning some geometric theorem, one of Euclid's students asked, "What is its use?" whereupon Euclid directed his assistant, "Give the young man a coin, he needs must be paid for his learning." Thus Euclid stated the precept that "usefullness" from inquiry into truth was only of economic value. I believe that this may have been a far reaching theorem and that its corollary implies the benefits of pure science to the spirit.

It is increasingly apparent that no strict or even qualified definition can differentiate physical from spiritual security. In the light of Greek history or of the present state of mankind, spiritual security cannot exist without physical security. Thus the gambit, offered by Euclid, is again challenged. I believe there is no defensible statement in "purity" of science or in the use of the words "applied" or "practical" or "artifactual" or "military" or "natural" or "unnatural" as applied to any basic difference of investigations into truth.

Let us not associate the matters which are called "directed" and "free" inquiry with the commonly used terms "applied" or "pure" research. This association is frequently met. I think that there is no veracity in believing that any un-directed inquiry exists. All workers attack problems that are directed by some compulsion. I believe that the only type of *directing* of research which is highly objectionable is that which insists on answers before understanding can be attained. On the other hand, certainly answers can be requested when understanding which is probably adequate *has* been attained. This understanding can be attained only by investigation on a broad front, for the threads of truth are pervasive and interweave in a fashion that can be understood only in retrospect.

Let me quote from the Fifth Annual Report to the American Cancer Society by the Committee on Growth:

> As scientific advisor to the American Cancer Society, it is the responsibility of the Committee on Growth to formulate and implement a comprehensive cancer research program. At first glance, the problem of what is and what is not cancer research, may appear to be a relatively simple one. It is true that a number of competent scientists have devoted themselves to the study of cancer and laboratories and institutions have been established for the sole purpose of investigating the cancer problem. Many of the most important discoveries related to cancer, such as x-rays and radium, however, were made by people who had no direct interest in cancer. There is no simple way to determine with any degree of certainty whether a particular research project will make important contributions to our knowledge of the nature and control of cancer.

In 1941, to illustrate, Dr. Charles Huggins of the University of Chicago announced his extremely important discovery regarding the treatment of cancer of the prostate in man by administration of female sex hormones. Although the treatment does not constitute a cure, in a matter of days or a few weeks after treatment is begun, all of the symptoms are gone in many instances and the patient feels completely well. The treatment may be effective for a period of several years.

The foundation for Dr. Huggins' discovery was laid in 1889 by Dr. Joseph Griffiths of Cambridge University in England. Dr. Griffiths, studying the seasonal changes in the size of the prostate gland in the hedgehog, noticed the decrease in the size of the prostate gland when an animal was castrated; this indicated a relation of the male sex hormone to the gland. In 1912, the basis for the second aspect of the problem was formed when Drs. Grosser and Husler, working at a children's clinic in Frankfurt, Germany, first discovered the enzyme, phosphatase, in the membrane lining the intestine. Drs. Steinach and Kun in 1926 demonstrated that the injection of female sex hormones into male animals caused a rapid decrease in the size of the prostate gland. In 1934, Dr. D. R. Davis in Wales and Drs. Baaman and Riedell in Stuttgart independently discovered that there were two different phosphatases, one active only in an acid medium and one only in an alkaline medium. A year later Drs. Kutcher and Wolbergs at the University of Heidelberg showed that the secretion from the human prostate gland was very rich in acid phosphatase. In 1938, Drs. A. B. and E. B. Gutman demonstrated that the blood of patients with cancer of the prostate often contained more than the normal amount of acid phosphatase. The basic information was now available to lead Dr. Huggins to undertake his highly successful studies on the treatment of cancer of the prostate with female sex hormones.

How many of the above investigators who made important fundamental contributions to this great advance in the treatment of cancer would have been supported by funds for cancer research had such funds been available? As a comment on the question, the following paragraph is quoted from the book Science and the Planned State, by Dr. John R. Baker of Oxford University in England:

> 'What central planner, interested in the cure of cancer, would have supported Griffiths in his studies of the seasonal cycle of the hedgehog, or Grosser and Husler in their biochemical work on the lining membrane of the intestine? How could anyone have connected phosphatase with cancer, when the existence of phosphatase was unknown? And while it was yet unknown, how could the men in charge of cancer funds know to whom to give the money for research? How lucky it is for sufferers from cancer of the prostate that Griffiths and Grosser and others were not doing cancer research!'

Certainly these men possess the humility to recognize their lack of understanding and the importance of a broad attack. How different from research "by the numbers"!

To victimize you further in your helpless position, but also to clarify my position to a degree adequate for your competent judgment, let me sketch a notion of the hierarchy of physical science and engineering. Central in this hierarchy are the studies of the great physical provinces, namely oceanography, meteorology, astronomy, and geology, drawing from all of the applicable established disciplines and proceeding toward an understanding of the complex processes in the provinces and their interrelations. Engineering is the study which, through its apprentice industry, reaps the results of the hierarchy for the *physical* benefit of man. Thus, whether it be fisheries, marine architecture, agronomy, applied mathematics, textile testing (or if you like, surgery), I will call it engineering in this broad sense.

In this picture, an established discipline, such as chemistry or genetics, is concerned with the study of apparently consanguinous aspects of several physical provinces. It is believed that these aspects are encompassed by some family of rules by which the worker may be able to answer the question: what will something do? In reality, a discipline attempts to set up an analogue of the parts or processes in one of several ways, depending on the complexity and developmental stage of the study. In complex cases, including most phases of biology, the discipline is an attempt to organize words in such a way that they will set up in the consciousness a mental analogue of the part or process, that is, to describe a static taxonomy or dynamic behavior. In the less complex subjects, such as physics, chemistry, hydrodynamics, physical oceanography, etc., an attempt is made to establish symbols and associated rules of counting which will cause numbers to behave like the physical quantities under study. Also, physical analogues are devised on the basis of assumed similarity of the counting laws, or descriptions of the model, to the part or process. That is, the disciplines attempt to establish a neural, symbolic or physical analogue which will re-enact processes in the past with the greatest attainable similitude so that other related future processes can be predicted with the greatest possible reliability. The symbolic approach is most capable of handling a number of rather simple and similar quantities that behave in simple rigorous ways, whereas the descriptive approach does surprisingly well with inductive results derived from description of a large number of highly dissimilar quantities which behave and interact in equally rigorous but highly complex ways. The great biological laws of evolution and biogenetic recapitulation have been induced from masses of description, although the inexpressible uncertainties of our understanding of biological processes are immeasurable compared with those expressed uncertainties of the uncertainty principle of atomic physics.

Frequently, in different disciplines the symbolic and descriptive approaches almost become fetishes. Both extremes certainly are suspect: the group which is content that the gyrations of its symbols truly explain events without the necessity of observation and visualization as well as the group which believes that a description can be improved only by making it more detailed, each without understanding the processes in both quantitative and descriptive realistic terms.

There are many present evidences of relaxation; the rigorous symbolists content themselves with statistical approaches while the documentists also utilize these possibilities. Analogue computors, including models, are increasingly important. Yet there remains a great middle ground which contains a large number of problems in oceanography and engineering whereto there seems to be no adequate approach. These are problems wherein the processes, materials, and interactions are so complex and uncertain as to permit no rigor and too difficult of observation to permit adequate description; *yet quantitative answers are required.* It is not that engineer and oceanographer are reactionary in their approaches—on the contrary, they have employed the best discoverable attack on their many problems but have been stultified to a degree by those groups that have adhered strictly either to symbols or descriptions without searching the middle ground. I believe that here we have a large and neglected area wherein engineering and oceanography together can benefit.

Let me quote a simple example. For many years the refraction of ocean waves was well known. The engineer encountered wave damage to his structures from wave forces that produced failure or erosion. The general descriptive understanding of the refraction process was well known. The fisherman's principle of "the points draw the waves" was adequate for many needs but it was inadequate for the location and design of structures on a headland. At the same time, rigorous expressions for wave refraction existed so that the "distribution of wave energy on a ridge with parabolic contours and exponential contour spacing" could be handled. Between these two extremes were the real world conditions where real waves peaked up and damaged installations on a point that looked like no point on a parabolic ridge yet devised. The simple solution to this problem resulted from the rational use of all that was known of wave refraction. From the description of offshore waves, laborious step by step construction was started, each step being determined by the quantitative laws and modified by the descriptive understanding. Realistic waves were brought in over realistic bottom topography to a realistic shoreline by a process in which a draftsman was taught to move a pencil as a wave moves. Many vexing questions were resolved in this process; for example, the effect of small bottom features was no longer open to argument since it could now be visualized. I am happy to note that this solution in no way froze the attack on wave refraction.

Aids which facilitated construction were devised for the draftsman yet room was left for the exercise of judgment. The documentists reported more observations on wave refraction and the symbolists set about explaining these with excellent results and with an advance of understanding.

This is a simple example. Surely better ones could be quoted. Yet, simple as it is, I believe the implications are important. I am impressed by the dichotomy of approach in many important cases. Let us go beyond the last example to the virtually unsolved problem of the impulsive loading of complex structures. I believe it probable that such impulsive loading of ships, buildings, automobiles and human bodies is rapidly becoming man's most import environmental condition.

Let us say a pier is destroyed by waves, or a ship by explosions. When a pier is destroyed, the engineer determines the probable height of the waves, describes the nature of the original structure and the nature of the damage, perhaps makes some static calculations on the strength of the installation, and proposes an increase in the factor of safety of some of its members from 3 to 5. On the other hand, the symbolist writes the equation for the impulse of a sinusoidal or trochoidal wave, approximates the characteristics of the pier as a cantilever, and then permits the two to interact according to certain rules governing harmonic motion. It is little wonder that opinions differ so widely. Actually the process is far too complex to be handled by either alone, whereas together the workers are capable of describing the events step by step, not losing sight of the realism of particles in either pier or water or of the drag on attached fouling organisms in contemplation of gyrating symbols; thus a visualization, tethered by quantitative calculations, could be carried through at the most fundamental level of process. What are the forces? What do the particles do? No doubt, in the case of the pier or ship, the symbolic approach could be enhanced by drawing from seismology and expressing transient waves (flexural, shear or torsional) which are generated and which move through the body in some idealized way. For these early purposes are these not artificialities? Is it not sufficient to know the forces and particle restraints and to trace through the process as laboriously as necessary in order to create a breakthrough in understanding the complex processes for future realistic, understanding methods and generalizations, as we have seen in the simple case of wave refraction?

To express this more clearly it would be necessary for me to quote more examples. I believe such an attack is applicable in oceanographic problems of mixing, evaporation, wind drag, productivity, sedimentation; in fisheries problems of population dynamics and availability; in naval problems of mine countermeasures and explosion damage; and in a host of other problems now being attacked from two aspects to the neglect of the middle ground.

I am sure that many persons will believe this to be a small point. Many are quite sure that present analytical or descriptive approaches are adequate. I will say that the approaches are slowly becoming so. Careful, thoughtful observations and rational "real world" approaches must sculp idealization. The consideration of fronts, ripples, bursting bubbles, white caps, surface slicks and spray as real conditions of the ocean surface will reveal the manner in which fluxes of matter and energy occur through the ocean-atmosphere interface in a way that never could be realized by the strict analytical approach. The scientists who have initiated this realistic work are to be congratulated.

To emphasize the degree to which our thinking is often circumscribed by the fictions that we have created, I would like to offer the challenge of two deceptively simple problems that I have been perpetrating on friends lately. One is for the oceanographer. How does a group of water particles at a depth in the ocean accumulate the pressure commensurate with that depth? And one for the engineers. How does an immersed vertical oceanographic cable reflect at the surface the total buoyant effect of the water over its length?

I pose these for fun. However, sometime, if you have the opportunity, consider them, not with vectors or free body conventions but with a realistic rational picture of how the water is aware of that lying above and how the cable can accumulate its information at the surface. You will be amazed at how meaningless become the fictions and smooth conventions with which we often limit the veracity of our thinking.

It is, of course, presumptious of me to discuss this matter so incompletely in the presence of so many whose understanding far exceeds mine. However, I believe I owe no apologies for the things for which I sue:

First, an unreserved recognition of the common brotherhood of investigation into truth, that there is no stigma of the "applied," indeed, that there is no defensible difference between the "applied" and the "pure"—in my opinion, any stigmata attach to "pure" science for having in a measure failed of its promise.

Second, the recognition that "free" untrammeled research is the scientist's responsibility rather than his license and that such research is demanded by the necessity to understand the complex weave of the threads of truth, which admits no extensive preconception of what is or is not important in an inquiry.

Third, that no relation needs to exist between the degree of application and freedom; but that serious lack of freedom always obtains when "directing" insists on a narrow attack or proceeds without understanding.

Fourth, a recognition of a great common ground of real world *problems amenable to unreserved rational attack by those of all groups who possess part of the truth and who themselves are morally responsible for their solution.*

Fifth, a free exchange of methods; tolerance and understanding of different approaches when brought to focus on an important problem.

In conclusion, I realize that this new structure and this community tell the tale better than I. For here exemplified is a community, a common brotherhood of scientists and engineers, bringing their energies to bear on the "somethings," many man-made, that we must understand and control for the security of mankind.

SEA TEMPERATURE VARIATIONS ASSOCIATED WITH TIDAL CURRENTS IN STRATIFIED SHALLOW WATER OVER AN IRREGULAR BOTTOM[1]

By

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ABSTRACT

Unusual features of the large and nearly periodic variations in sea temperature which are observed in shallow stratified water along the coast of southern California may be caused by tidal stirring over an irregular bottom and by subsequent horizontal and vertical oscillating movements associated with tides.

PART I

Sea temperature variations having an average diurnal range of approximately 4° C during summer months are indicated on thermograph records obtained at the end of Scripps pier in the years 1926 through 1931. Other observations show that cold spots are found in certain localities along the coast, that the vertical temperature structure changes markedly with position, that the amplitude of local temperature variations changes systematically from week to week, and that large local temperature changes occur in a short time. The records have been analyzed here to determine the time, the frequency and the range of the variations at different depths and in different months. Analysis of the data and further investigations led to a theory which, when considered together with effects of the normal wave action associated with tides (see Arthur, 1954), accounts for most of the features of the variations. This theory makes use of a formula developed by R. H. Fleming for tidal current velocities in shallow water. The formula indicates that, in certain regions, widely different velocities may be found adjacent to each other. The differences lead to formation of eddies which, over irregular bottom, cause stirring. In highly stratified water, such as that found off southern California in summer, this bottom stirring causes cooling in the upper layers or tends to intensify vertical temperature

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[1] Contribution from the Scripps Institution of Oceanography, New Series No. 746, and from the Department of Oceanography, A. & M. College of Texas, Oceanography and Meteorology Series No. 60, based in part upon investigations conducted for the Office of Naval Research (under contract with the University of California and the Texas A. & M. Research Foundation).

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gradients in any overlying thermocline. Oscillating tidal currents then cause the "cold spot" thus formed to migrate back and forth so that large temperature variations are observed in any locality where the cold water mass, during its horizontal migration, replaces normal unstirred waters. The intensification of the temperature gradient in the thermocline also results in more marked local temperature changes associated with vertical oscillations of the water.

In the following discussion, the proposed theory and a description of the kind of predictions which it permits establish a framework into which the various supporting empirical features may be fitted. Further details may be found in a dissertation by Leipper (1950).

Since tidal currents vary according to the stages of the tide, it is convenient to fix attention upon velocities at a certain tidal stage. In the following, attention shall be centered on the tidal stage having the maximum tidal-current velocity.

Intuitively, one would expect the maximum velocity of tidal current near shore on a continental shelf to be proportional to the distance from shore and to be inversely proportional to the wave period and depth, i.e.

$$V_{\max} = \frac{kx}{Th},$$

where x is the distance from shore, h the depth, T the wave period, and k a constant. Such a relation may be developed from physical considerations.

By using an expression derived by Lamb (1932: 254–256) from the equations of motion and from the equation of continuity and by introducing certain assumptions which seem reasonable for the continental shelf, Fleming (1938) developed a method for computing the maximum tidal-current velocity. It is assumed that the tidal amplitude is nearly constant over the small area near shore, that the wave length is great compared to the distances under consideration, and that the wave is a standing wave with node line parallel to the coast. The expression for the maximum velocity of the tidal current is then given by equation (2), where the constant k in equation (1) becomes the product of 2π times the wave amplitude η

$$V_{\max} = \frac{2\pi\eta}{T}\frac{x}{h}. \tag{2}$$

A quantity C may be defined as

$$C = V\left(\frac{T}{2\pi\eta}\right). \tag{3}$$

That is, from equation (2), $C = x/h$.

When we examine charts showing details of bottom configurations in a band approximately five miles wide along the California coastline, we observe that many localities have configurations which, in the light of equation (2), lead to widely different tidal current velocities in areas not far removed from each other. Any locality where the spacing of the inshore bottom contours change suddenly along the coastline has associated velocity variations. Such changes in contour spacing are often observed where a point of land juts seaward. Different velocities in adjacent areas tend to cause a turning of the currents, the stronger one running ahead and turning toward the weaker; thus eddies are formed.

Mechanical stirring occurs in the presence of tidal currents. For example, Sverdrup, et al. (1946: 566–569), in discussing the effects of the bottom, have explained that currents must be deflected vertically or horizontally by submarine peaks. The stability of the water, the strength of the current, and the configuration of the peaks determine the amount and direction of deflection. Quantitative estimates of such modifications of tidal currents in shallow water and the effect of these modifications on the mixing processes have not yet been made.

Since the above difference between the velocities of maximum tidal currents is due to a difference in bottom slopes and since the resulting eddies form between the different currents, the eddies are formed over a region of changing bottom slope where they must have some associated vertical movement. Such movement intensifies both vertical and horizontal stirring of waters of different temperatures.

If the waters are nearly homogeneous, as is often the case in the upper layers during winter, stirring related to tidal currents has little or no effect in bringing about local changes in temperature. However, in summer the surface layers may become highly stratified. Stratification may be particularly marked in regions where cold upwelled water approaches the surface but where normal heating occurs at the surface. Under these circumstances any vertical stirring may markedly cool the surface layers. Thus, in summer we may expect a cold spot to develop over an area where bottom contours are favorable for variation in tidal currents, with consequent stirring and mixing. It is possible that the stirring action will occur in the underlying water only and will not reach the surface. In this case a shallow and more intense thermocline develops which may define a cold spot at some level below the sea surface.

In most localities the wave period of tides does not change significantly from day to day whereas the amplitude does. Since the maximum velocity of a tidal current is directly proportional to the amplitude [eq. (2)], the local velocities also change from day to day. This causes changes in the intensity of eddying movements and in the amount of related stirring action. Thus, in any region where bottom contours favor the formation of eddies and where temperature stratification exists, it is to be expected that a cold spot will form and will increase in extent from day to day while the tidal range and the corresponding tidal mixing decreases.

As noted, the maximum tidal-current velocities at a given distance from shore are greatest where the depth is least. Thus the amount of stirring associated with these currents would be greater in shallow water. Also, in depths below the thermocline, the vertical temperature gradient is relatively small and a given amount of stirring here leads to smaller local temperature changes than at shallower depths where the temperature gradient may be larger. It is true that the greater stability in the thermocline region opposes vertical mixing. However, this is not significant in the face of the energy available in the currents related to the tides, and it may be expected that the largest temperature changes caused by tidal currents at a given distance from shore will occur in the shallowest waters where the vertical temperature gradient is largest.

Regions having large temperature changes associated with tidal stirring are limited in size. Limiting factors are: the dimensions of the area having bottom contours favorable for stirring; the size of the region having highly stratified water; and the distance which water migrates in a tidal cycle. Consideration of these factors leads to the conclusion that cold spots would be expected to have diameters not greater than approximately three miles.

Because of the nature of the currents in the region in which cold spots are formed, the spots must migrate or move with the tides. The astronomic tides are periodic, being semidiurnal in most regions, and the vertical and horizontal movements which are required to permit the rise and fall of the water level in tidal action are the tidal currents which affect the cold spots. These currents must also be periodic and oscillating, the periods being the same as those of the tides unless the currents are modified by other influences.

In a given locality the tidal current at a certain stage in one tidal cycle may be different from that at the same stage of other cycles. Differences occur which are related to the change in tidal amplitude and to the influence of varying local ocean currents not related to the tide.

Since cold spots are produced by stirring in tidal currents, they always exist in regions where they cannot remain stationary. They must move with these currents, migrating back and forth in a time equal to a tidal period. The distance of such migration depends on the average tidal-current velocity. This is usually less than one-half mile per hour, thus limiting the migration of a cold spot in a semidiurnal tidal cycle to less than approximately three miles.

Seasonal or wind-driven currents which change their direction or speed but which are not related to the tides sometimes aid and at other times hinder the tidal migration of a particular cold spot toward an observation point. This accounts for the cold dip at a given locality occurring sometimes at one tidal stage and sometimes at another.

Since cold spots are formed by turbulence over an irregular bottom, their three-dimensional structure will be dome-like, with the broadest extent of mixed water and the lowest temperature in the deepest levels. As such a dome or crest moves toward a point of observation, decreasing temperatures will be noticed first at the bottom. As the dome pushes forward, the cold water will be observed at progressively shallower depths until the dome crest arrives at the observation point, at which time some of the original warm water mass may or may not remain above the dome. As the dome recedes, the warm water will return first at the surface and then will gradually occupy the greater depths.

The foregoing considerations permit the extrapolation of certain observed local temperature trends with greater accuracy than has been possible previously. For example, we may predict that the local temperature range in regions having cold spots will increase as stratification increases and that it will decrease as the waters of the surface layers become more homogeneous. Also, if temperature dips have been observed from day to day at a given tidal stage, we forecast that the next dip will occur at that same stage of the predicted tide, assuming that no significant change occurs in the wind or in other nonperiodic phenomena. In extrapolations, use may be made of day to day trends in the amplitude of temperature variations which are associated with increasing and decreasing tidal ranges.

Horizontal distributions of temperature in shallow water often may be explained or predicted by considering the tides, the water stratification, the bottom topography, and the tidal stirring process.

PART II

Data collected from 1916 to 1950 under the supervision of Dr. George F. McEwen have been used to study the validity of the model for temperature variation described above. These data include: daily sea-surface temperatures collected for more than 30 years at selected points along the coast; four years of thermograph records taken 2 feet and 16 feet above the bottom at the end of the 1100-foot Scripps pier; hydrographic observations taken 5 miles and 11 miles west of the pier at two-week intervals over a period of several years. Following an analysis of these data, which brought to light several unusual and marked types of variation in the shallow-water temperatures, additional observations were planned and carried out over a two-year period to supplement the McEwen data and to provide information that was needed to serve as a further check on the explanation for the observed variations. (Bathythermograph [BT] records are in degrees Fahrenheit, the other records in degrees Centigrade; for convenient comparison with other data summaries, both of these respective units have been retained in this analysis.)

The quantity C, defined in eq. 3, has been computed for various locations off La Jolla, California by using a chart that shows bottom topography. Lines of equal C value (i.e., lines of constant relative theoretical velocity of maximum tidal current) have been drawn in Fig. 1. It is evident that there is a great variation in the value of maximum velocity with position. West of La Jolla, velocities are as much as 3½ times greater than those north and northwest of La Jolla. A similar chart prepared in greater detail showed velocities in one area which were 9 times greater than those in a nearby area.

To obtain observed values for comparison with theoretical current velocities, simultaneous drifts of two submerged triplane buoys in a 3-hour interval between low and high tide were carefully plotted. The buoys were released in regions that were computed to have quite different tidal-current velocities, the ratio between velocities being approximately 7 : 3. The two paths of drift are shown in Fig. 1. The ratio of two *total* drifts was 3.26 : 1, that of *net* drifts (distances from beginning to end points) 2.19 : 1. The theoretically computed ratio of 2.43 : 1 compares favorably with observation, and the theory is supported. The observed velocities were from 0.2 to 0.6 knots.

Drift observations were carried out by John Blankenship who took particular care to eliminate the effect of wind on the buoys. The day selected was November 10, 1948, with a low tide of 2.5 feet at 1248 PST and a high tide of 4.3 feet at 1746. Buoys, dropped one hour after low tide, were picked up 58 minutes before high tide. Note in Fig. 1 that the drift was generally toward the southeast while the tide was rising.

The significant features of the seasonal temperature variation are indicated by the temperature-depth structures in Fig. 2, in which curves for winter and summer are compared. In Fig. 2a the curves were obtained by averaging all available BT observations taken in

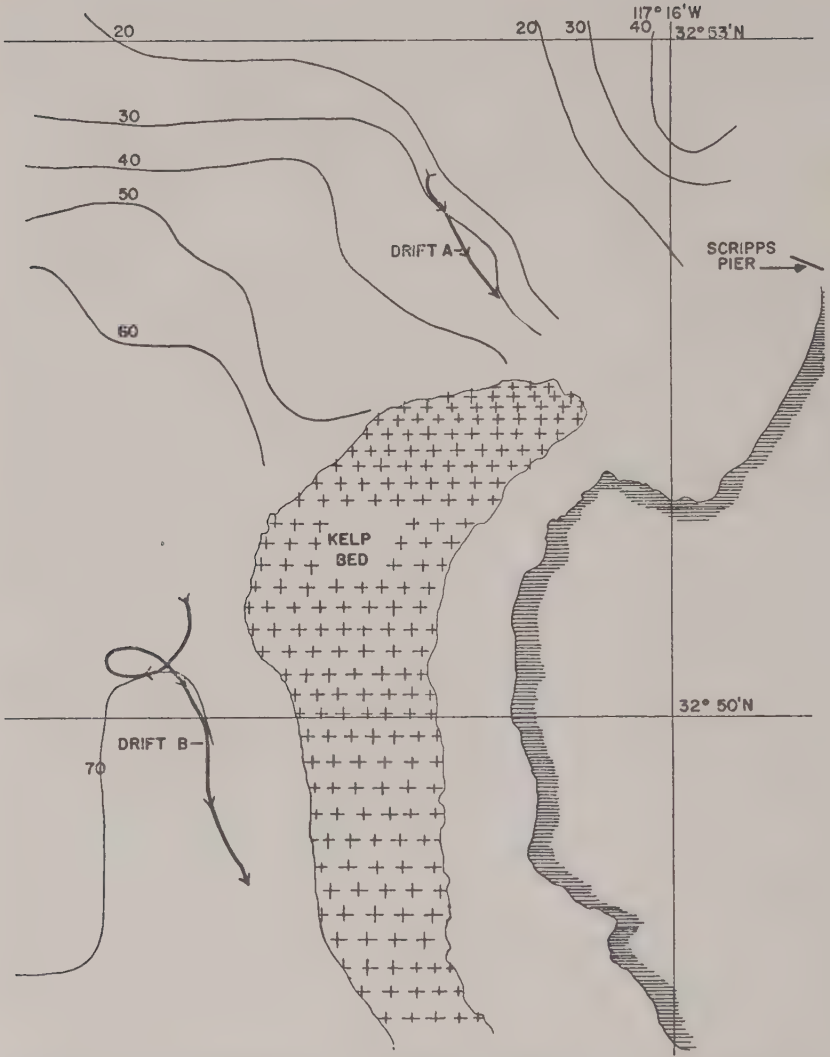

117° 16'W
32° 53'N
20
30
40
20
30
40
50
60
70
DRIFT A
SCRIPPS PIER
KELP BED
DRIFT B
32° 50'N

Figure 1. Simultaneous drifts of two submerged triplane buoys in a 3-hour interval between low and high tide; also, lines of constant relative theoretical velocity of maximum tidal current.

August and also in February from a region about 24 miles offshore. Above 100 feet the change from winter to summer is more or less typical of most ocean areas, with nearly isothermal water of low temperature in winter and more stratified water with higher surface temperature in summer. From 100 to 400 feet, however, the change is opposite that which might be expected in most regions, since the temperature in summer is lower than that in winter. This change is even more apparent in the example in Fig. 2b which is based on two single hydrographic observations made at the same place in March and June; all of the water below about 10 m dropped in temperature during the March–June interval. At about 30 m the temperature was about 5° C lower in summer than in winter. This type of variation, common to the region off southern California, has often been described (McEwen, 1916: 352–353, fig. 985). It has been explained that this phenomenon is due to upwelling brought about by strong northwesterly winds in the springtime north of Point Conception. After upwelling, this cold water flows southward and is gradually warmed through a thin layer near the surface; when it arrives in the southern California area, the temperature-depth structure in summer has the appearance of the June and August curves shown in Fig. 2.

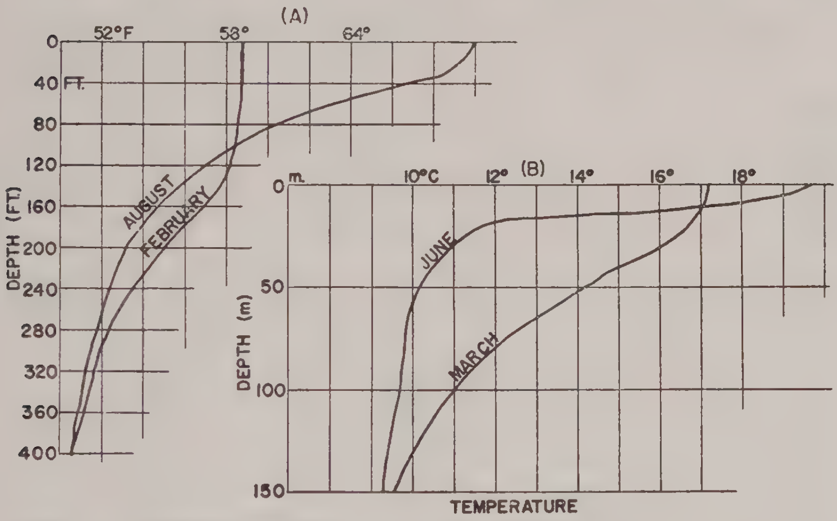


Figure 2. Comparison of winter and summer temperature-depth structures offshore near Scripps Pier.

The combination of normal surface heating and abnormal cooling

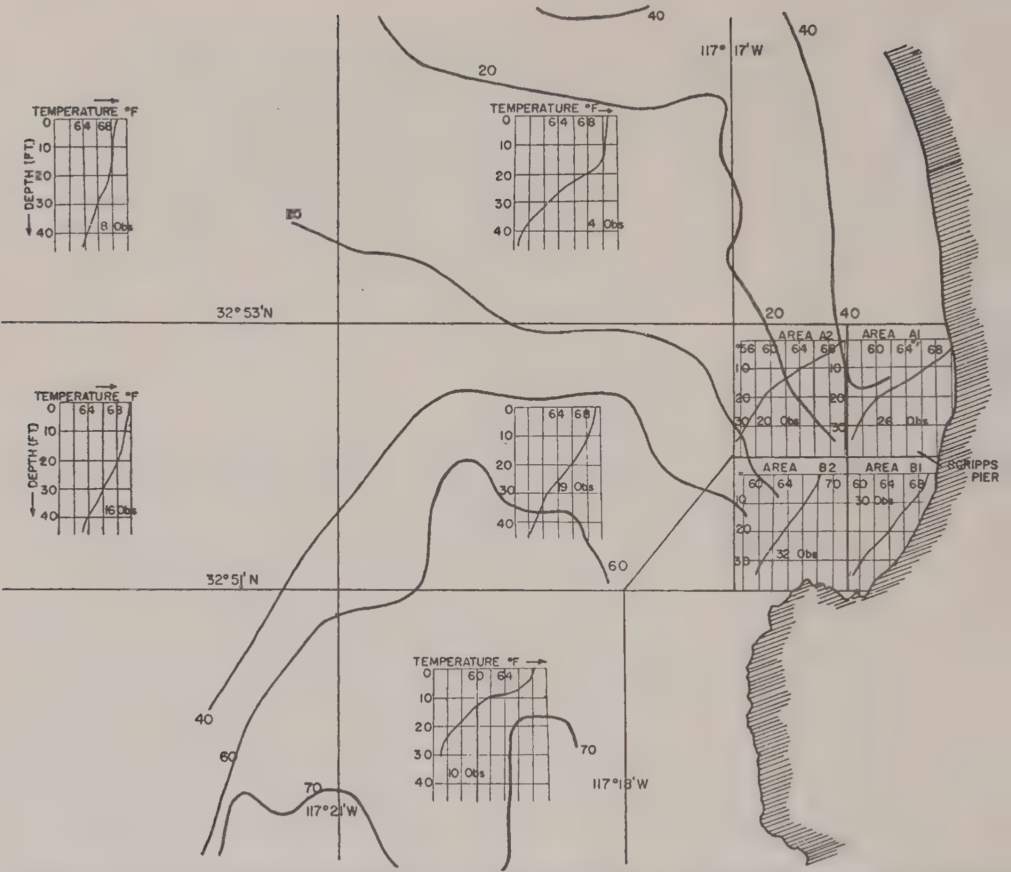

40
40
117° 17'W
20
TEMPERATURE °F
DEPTH (FT)
0
10
20
30
40
64
68
8 Obs
4 Obs
20
32° 53'N
20
40
AREA A2
AREA A1
56
60
64
68
20 Obs
26 Obs
AREA B2
AREA B1
SCRIPPS PIER
70
30 Obs
32 Obs
16 Obs
19 Obs
60
32° 51'N
10 Obs
70
117° 18'W
40
60
70
117° 21'W

Figure 3. Average temperature-depth structure in summer in different areas near Scripps Pier; also, lines of constant relative theoretical velocity of maximum tidal current.

which is indicated at some depths below the surface results in a sharp temperature contrast between the surface layers and those immediately below them. This contrast sets the stage for the development of local cold regions near the surface when the two layers are stirred in places by varying tidal currents.

Another important feature of the temperature distribution is that the temperature structure of the water near shore differs from that farther out. For example, Fig. 3 shows that the vertical temperature gradient in summer near the surface off Scripps pier is much greater than that farther offshore. For the 0 to 30-foot depth interval, the average temperature decrease with depth along the coast is always 8° F (at times greater than 14°) for the regions shown, whereas in offshore areas the average decrease is only 3° F. Thus, along the coast a given stirring of the surface waters might result in a large temperature decrease, whereas farther offshore, where the water is more nearly isothermal, the same amount of stirring would change the surface temperature but little.

In winter, vertical temperature differences are small over the entire area, being usually less than 1° F per 30 feet of depth. Hence a given amount of stirring could result in only a small decrease in surface temperature; furthermore, the possible temperature drop brought about along the coast would not be appreciably different from that in the region offshore.

TABLE I. Average Monthly Diurnal Range of Sea Temperature at Scripps Pier (°C)

Month	*J*	*F*	*M*	*A*	*M*	*J*	*J*	*A*	*S*	*O*	*N*	*D*
2 feet above bottom	0.5	0.5	1.0	1.3	1.4	1.3	1.8	1.7	1.6	1.0	0.5	0.4
16 feet above bottom	0.6	0.7	0.9	1.2	1.2	0.9	1.6	1.3	1.3	0.9	0.6	0.6

On 19 days throughout the year, series of observations were made at one mile intervals on a line perpendicular to the coast extending 10 to 15 miles offshore. Temperature-depth sections of these data showed 18 sections with isotherms rising toward shore. This appears to be a general tendency.

To compute the average amplitude of the diurnal temperature variation on ordinary calendar days, values were read from the Scripps Pier thermographs at two-hour intervals beginning at midnight; monthly averages were then calculated for each hour read. The difference between the lowest and highest average for a given month is the diurnal range for that month. Monthly ranges were computed for three separate years, and these were then averaged together by months (see Table I).

Note two unusual features of the data in Table I. First, from March through October the diurnal range of variations near bottom is greater than the range 16 feet above bottom. Since solar radiation is absorbed rapidly near the surface and since only about 6% of it reaches a depth of 5 m or 16.8 feet (Sverdrup, et al., 1946: 107), an important diurnal process other than radiation is indicated. Second, the diurnal ranges in July near the bottom are large, reaching a value of 1.8° C or 3.2° F. The maximum average diurnal variation caused by solar heating is smaller and may be calculated approximately by assuming that the incoming energy is uniformly distributed by intense mixing throughout a surface layer 5 m in depth. Using the maximum average insolation at the Pier, 484 g cal/cm² (McEwen, 1938: 236), the maximum daily increase in sea temperature at a depth of 5 m is 1° C. The increase which would be expected is considerably less than this because of heat lost by evaporation, conduction and radiation from the sea surface. Thus the observed variation is much larger than that due to the processes usually considered.

At the Scripps pier the temperature variation within a given day, strangely enough, is more regular in winter than summer. In summer it is masked by other types of temperature fluctuations, including a series of dips which usually occur daily at intervals approximately equal to tidal periods. See Fig. 4 for an example of temperature variations observed during a week in the summer of 1928 together with the associated heights of the tide. The dips shown on the thermograph traces do not have the appearance of sinusoidal variations; many of them are of the type which might be expected when one water mass is rapidly replaced by another of different temperature. In some cases, changes as great as 7° C occur in periods as short as 15 minutes. As these dips increase in size from day to day, the average temperature as well as the daily maximum at Scripps pier decreases (see Fig. 4).

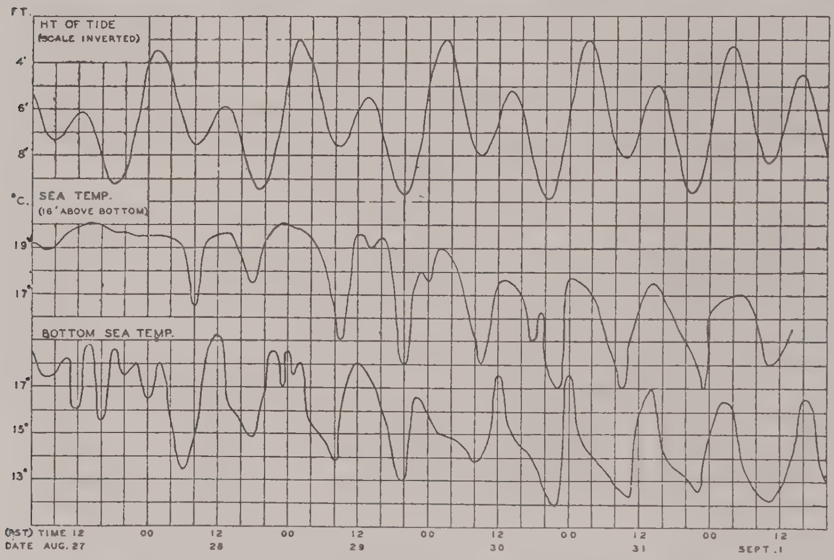


Figure 4. Tide and sea temperature variations at Scripps Pier, 1928.

Variations of the type shown in Fig. 4 are absent during winter, and their nature varies considerably from day to day and from week to week during the summer months. In 1928 the lowest temperatures occurred regularly with the high tide. In other weeks, however, they occurred with the low tide. As will be shown, the former occurrence is more common, but cases where the coldest water is associated with every stage of the tide have been observed. Correlation by harmonic analysis should not be attempted because of the obvious shift in phase.

Tabulations show that the majority of maximum daily temperature dips occur during the night. Since these dips appear to be related to tidal currents, diurnal characteristics might be expected when it is considered that the solar tidal component is 43% of the lunar component and that tidal currents are subject therefore to a large diurnal influence. The regular occurrence of the larger nocturnal dips lowers the night-time average temperatures and thus increases the amplitude of the ordinary diurnal variation.

To study temperature variation within diurnal tidal periods, time was counted from one high tide to the second following high tide. In this manner 'tidal days' were defined as 24 to 25 hours in duration.

A frequency diagram in Fig. 5 shows the number of times that dips occurred on each hour of the tidal day. Fig. 5a is based on only the maximum dip which occurred each day, while Fig. 5b is based on all distinct dips, usually two for each day. Greatest frequencies were observed at approximately 0000 and 1200 h, which corrrespond to high tides. Least frequencies were observed at about 0600 and 1800, the times of low tides. Of the total number of dips, 55% occurred within two hours of the high tide while only 24% occurred within two hours of the low tide. For given series of successive days, the time of the dips did not shift erratically in the tidal time scale.

An effort has been made to determine under what conditions temperature dips may be expected at high tide and under what conditions they may be observed at other times. There appears to be a systematic seasonal deviation of the time of occurrence from the time of high tide as the year progresses (see Leipper, 1950).

To study further the tidal effects on temperature, the ordinary diurnal heating was eliminated. Average monthly temperatures were obtained for each 2-hour period of the day, and the sine curve of best fit was drawn through the 12 averages. It was assumed that this curve represented the ordinary diurnal variation; deviations from the monthly mean shown by this curve at various hours of the solar day were used as corrections to the observed temperature values to eliminate the diurnal effect.

On each tidal day the temperature range was obtained by subtracting the minimum from the maximum, using the adjusted data.

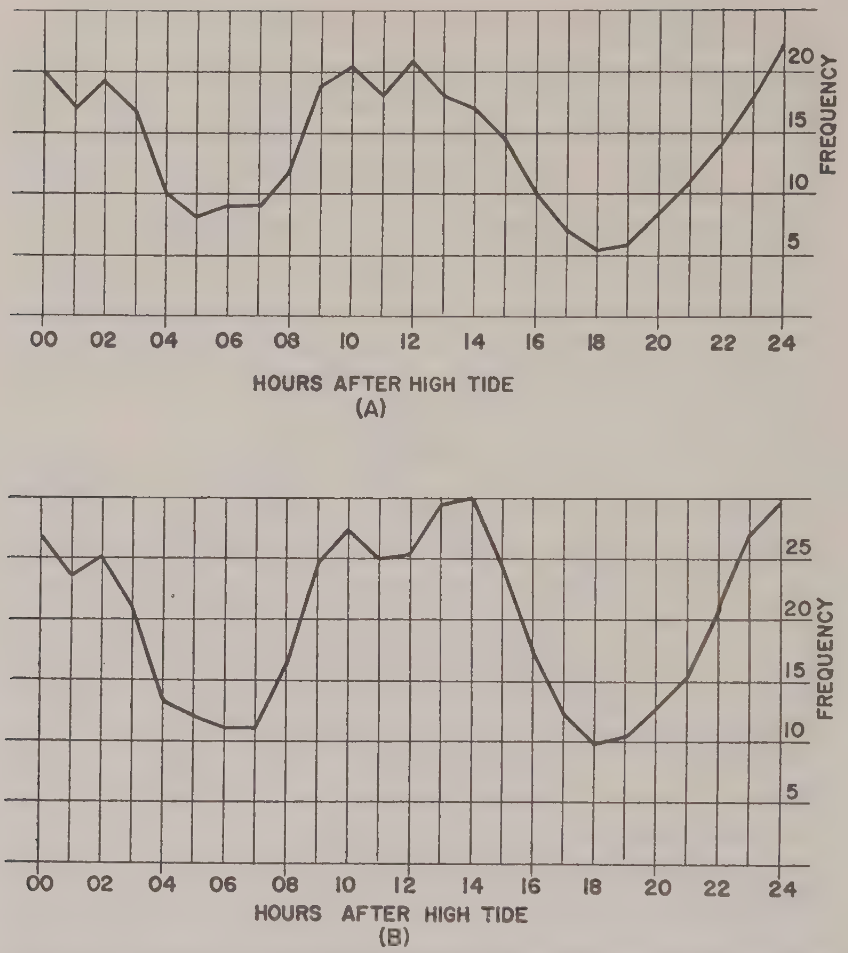


Figure 5. Frequency of occurrence of temperature dips at Scripps Pier in different one-hour intervals after high tide.

Ranges were then averaged by the month (see Fig. 6a). Data for the near-bottom changes are presented, since changes at this level are more marked and more consistent than those at the upper level. In winter the temperature range on tidal days is small, but the range increases in spring, and in summer it averages more than 4° C (see Fig. 6a). On the original thermograph traces it is difficult to observe any dips in December, January and February. During summer, dips have occurred on individual days which have lowered the temperature at Scripps pier below the lowest values observed in winter months.

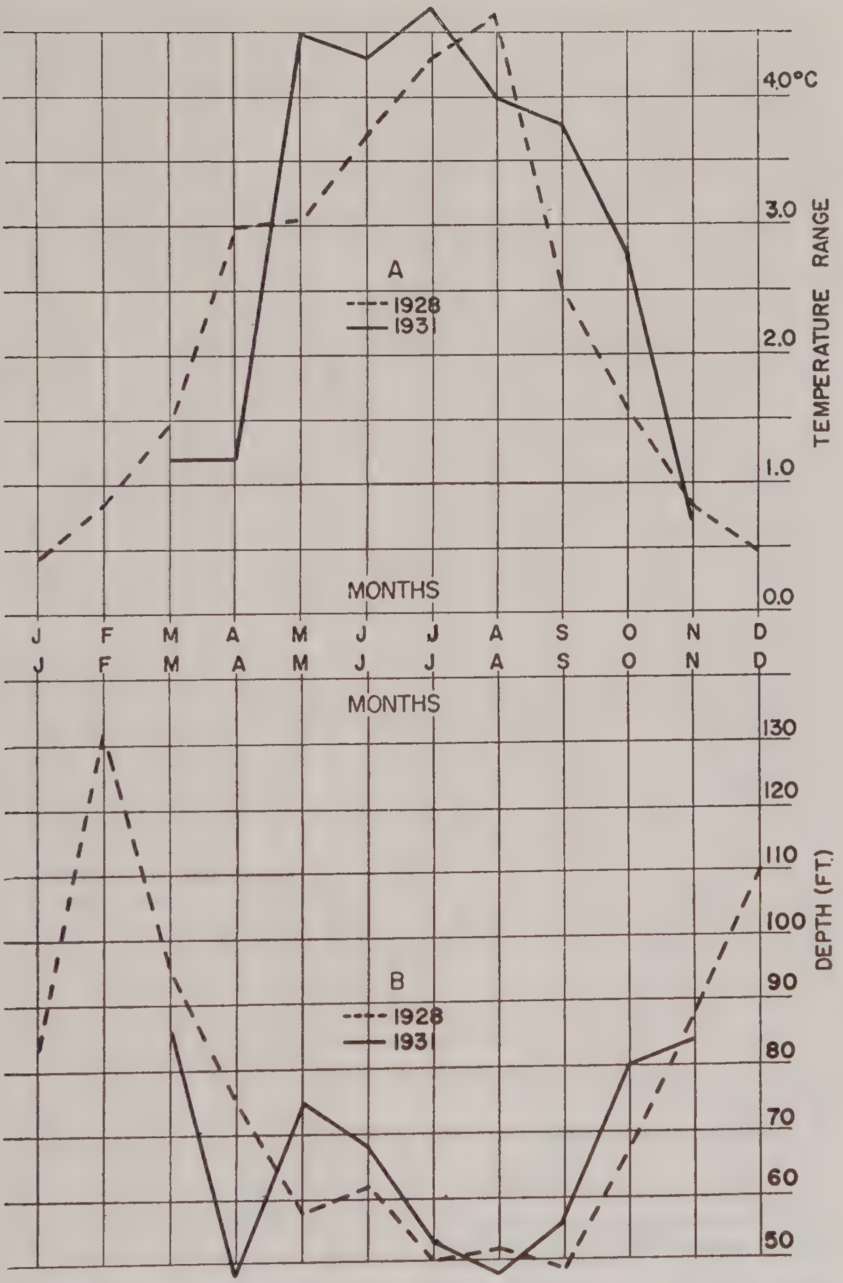


Figure 6. Monthly average range of sea temperature at bottom, Scripps Pier, on tidal days. Depth of water offshore which is colder by the amount of the average daily tidal deviation than the average observed at the bottom.

As noted, the presence of cold upwelled water near the surface in summer together with vertical and horizontal tidal movements can result in large local temperature dips. As shown in Fig. 6b, water as cold as that observed in the average cold dip in summer at the pier may be found within 50 feet of the surface off the San Diego area. (Offshore temperatures for this comparison were obtained by averaging BT observations taken about 24 miles from the coast.) Fig. 6b also shows that, although the dips in spring and fall lower the temperature an average of only about 1° C, water comparable to that which is colder than the average by one degree at the pier bottom cannot be found offshore in these seasons at less than 80- to 90-foot depths. Water with a temperature that is low enough to cause the extremely cold summer dips is closer at hand than that required to cause the moderate dips in fall and spring.

TABLE II. Ratios of Monthly Average Amplitudes and of Durations of Temperature Dips 2 Feet Above Bottom to Those 16 Feet Above Bottom

		J	*F*	*M*	*A*	*M*	*J*	*J*	*A*	*S*	*O*	*N*	*D*
Amplitude Ratio	1928	—	0.7	0.8	1.3	1.4	1.6	1.4	1.5	1.3	1.0	0.9	—
	1931	—	—	0.5	0.7	1.4	1.8	2.6	3.3	2.0	2.4	1.8	—
Duration Ratio	1928	—	0.8	0.9	1.1	1.2	1.4	1.3	1.3	1.0	0.8	0.8	—
	1931	—	—	0.3	0.8	1.1	1.4	1.5	1.8	1.5	1.6	1.0	—

The relative magnitudes of tidal changes in near-surface and near-bottom temperatures were analyzed by defining two ratios: (1) that of bottom to surface temperature change, called the 'amplitude ratio,' and (2) that of the duration of bottom dip to surface dip, called the 'duration ratio.' Ratios were computed from data which were not adjusted for diurnal variation, since the diurnal effects near surface and bottom were found to be nearly equal.

For 1928 and 1931, the amplitude ratio had minimum values in winter, maximum values in summer (see Table II). In winter the amplitude is greater near the surface than near the bottom, but in summer the situation is reversed and the near-bottom change may be more than three times that near the surface. The larger values of the 1931 ratio are probably associated with the fact that this was one of the warmest years on record; it is quite likely, therefore, that this was one of the years when the vertical temperature gradient was unusually high.

The trends of the duration ratio are similar to those of the amplitude ratio, but the variation is not quite so great. The monthly values of this ratio are also shown in Table II. Except when the deeper observation is at the depth of a strong thermocline and when internal waves are present, the amplitude and duration ratios for most parts of the ocean would be less than unity, since nearly all factors that affect sea temperature have their maximum influence at the surface. The fact that the pier ratios are greater than unity demonstrates that interval waves, tidal oscillation, or both are present.

If the theory presented is applicable at Scripps pier, then it should be possible to locate a cold region which would be close enough to the pier to be carried in and out from the pier by tidal migrations. Since such migrations are about three miles, a cold region should exist within a few miles of the pier area. In an attempt to locate such a region, a series of temperature observations were made in the summer of 1947 with surface bucket thermometers and BTs.

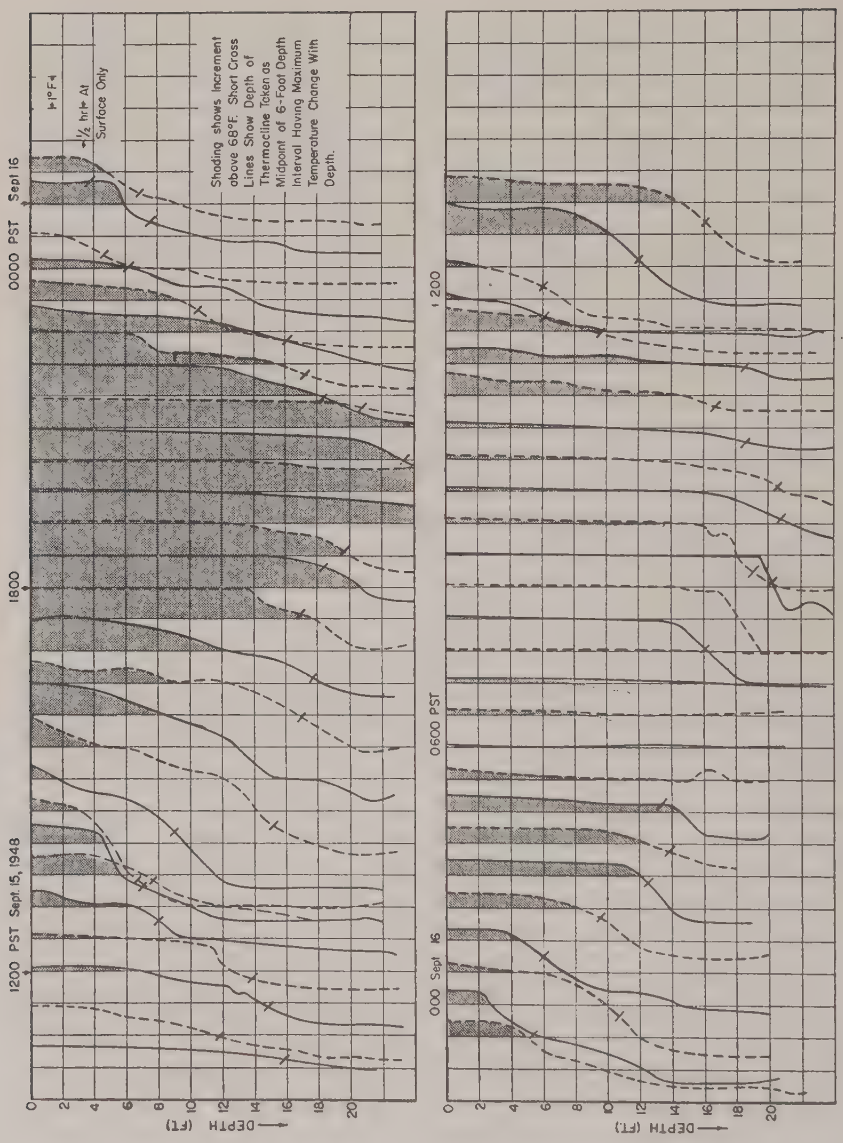
It was hoped that the cold areas could be located by use of surface temperature data alone, but this did not turn out to be the case, since in this particular area the mixing appeared to take place largely just beneath the surface. However, it was found that BT observations in certain regions were markedly different from others in adjacent regions (see Fig. 3), and that these differences would lead to the expected local temperature changes during tidal migrations. This variation in structure may be explained by considering the variation in maximum tidal current velocity with position, shown also in Fig. 3.

It was possible to make a series of observations showing the relation of cold dip to currents.

For a short time in 1947 a thermograph was again installed at the end of Scripps pier. By observing the variations indicated by this instrument and by considering the nature of the fluctuations shown by past records, it was possible to predict that a cold dip would occur about noon on July 25. The dip occurred as expected. Observations of it were made by B. K. Couper with a 40-foot BT and a bucket thermometer. Currents were determined by the movement of wooden chips thrown onto the water. The dip persisted from 1324 until 1557 PST, during which time the currents were toward the southeast and south. High tide occurred at 1525. At 1625 the currents had begun to shift and the temperature had begun to change. At 1725 relatively isothermal warm water was observed and the currents were toward the east and east-northeast.

To ascertain the temperature-depth structure over a 24-hour period, a series of BT observations was taken from the Scripps pier at half-hour intervals. From these it is possible to determine the temperature variation at any depth (see Fig. 7).

Variations were plotted for the depths 2 and 16 feet above bottom and it was found that the resulting curves were typical of many obtained on the thermographs. It was apparent that large dips did



Shading shows Increment above 68°F. Short Cross Lines Show Depth of Thermocline Taken as Midpoint of 6-Foot Depth Interval Having Maximum Temperature Change With Depth.

Figure 7. Half-hourly bathythermograms at the end of Scripps Pier.

occur, that these were of approximately tidal period (except for an irregularity at 0730 on September 16 at the bottom), that the smaller dips and those of shorter duration occurred at the surface and at the upper level, and that the ranges are approximately of the correct magnitude for comparison with the average for September shown in Fig. 6. Thus, comparison showed that these BT observations indicate the structural changes which occurred on other days when temperature dips were indicated at two fixed depths by thermographs only.

On the same day as the BT observations used in Fig. 7 were made, Dr. Donald Pritchard[2] arranged to have two ships make similar observations at 18 miles WNW and NW of the Scripps pier. Variations in depth of the thermocline at these positions and at the Scripps pier were determined and plotted. From these data three conclusions could be drawn. First, internal waves having a period of approximately 12 hours occurred at all three locations; second, the range of vertical motion was as great as 40 feet; third, the thermocline was found at a greater depth offshore than at the pier.

Further information on the nature of internal waves near shore was obtained from BTs obtained by a vessel which went out and returned along the same path, repeating observations in the same locations on both legs of the cruise. The temperatures at given longitudes changed markedly between outgoing and return trips.

In August 1948 a cruise to Lower California observed the width of certain low-temperature areas which had been found by Dr. Carl Hubbs along the coastline. In one observed area close to the coast the temperature averaged 58.4° at four stations and in another area 57.2° at six stations, while all of the temperatures seven miles or more offshore, except one, were above 64° F. The width of these near-shore low temperature bands was approximately two miles, and progressing seaward, a transition band of about five miles was measured before the warmer offshore water was reached. From shore seaward, the isotherms dropped so rapidly that the water inshore was many degrees colder than that observed at any depth down to 45 feet at the seaward end of the BT sections across these cold regions. In one section, the inshore stations were somewhat warmer than those a short distance offshore, indicating that the major cooling effect had not occurred at the immediate coastline in this locality. Comparing pier temperatures with values some 15 miles offshore, it is apparent that the maxima of surface temperatures at the pier from April through August occur at times when the water from the coast outward is of uniform or nearly uniform temperature.

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[2] Then at the U. S. Navy Electronics Laboratory at San Diego, California.

On the the other hand, when a dip occurs at the pier, the inshore water seems to be much colder than that offshore. This supports the conclusion that offshore changes are more gradual and less marked than temperature changes within one or two miles of the coast and it indicates further the presence of cold dips near shore.

CONCLUSION

The erratic nature of certain coastal sea temperature records which are based on a few observations at specific times of day are explained by the action of internal waves and by periodic migration of cold spots formed over shallow regions of irregular bottom by horizontal variations in velocity of tidal current in the presence of stratified water layers. Proper understanding of the observed variations greatly increases the value of coastal observations. Such observations should be fully utilized since they may readily be obtained from the shore or from piers and docks.

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Reprinted from Archives of Biochemistry and Biophysics
Volume 54, No. 1, January 1955
Academic Press Inc.
Printed in U.S.A.

Comparative Studies of Chromatographically Separated Phycoerythrins and Phycocyanins

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Comparative Studies of Chromatographically Separated Phycoerythrins and Phycocyanins[1]

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Received April 21, 1954

INTRODUCTION

The nomenclature system originally proposed by Svedberg and Katsurai (1) for the bile pigment chromoproteins of algae designates phycoerythrin or phycocyanin characteristic of the red algae (Rhodophyta) and the blue–green algae (Cyanophyta) by the prefixes R- and C-, respectively. Although the literature contains many references (2–5) to pigments other than the four commonly accepted varieties, their individuality has not been definitely established, largely because of the lack of refined analytical techniques.

A promising method for the resolution of the algal bilichromoproteins[3] has recently been provided by Swingle and Tiselius (8) and Krasnovskii *et al.* (9) which involves adsorption of the pigments on tricalcium phosphate columns and development with phosphate buffers. Comparative studies of the water-soluble extracts from a variety of red and blue–green algae, communicated below in brief, have indicated the general usefulness of chromatography in the analysis of pigments of this group,

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[1] Contribution from the Scripps Institution of Oceanography, New Series 747.

[2] Part of this work was carried out during the tenure of an award from the Lalor Foundation.

[3] The term *bilichromoproteins* is here proposed as a general name for those naturally occurring proteinaceous pigments in which the chromophoric group is related to the bile pigments. This designation seems preferable to the term *phycochromoproteids* introduced by Kylin (6) as a general name for phycoerythrin and phycocyanin, which would include, properly speaking, other algal chromoproteins, e.g., chloroplastin, carotenoid–protein complexes, etc. Some of the recent literature uses *phycobilins* to designate the algal bile pigment chromoproteins, but it would seem desirable to retain this term for the chromophores as originally intended by Lemberg (7).

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and have revealed the occurrence of individual pigments other than the classical varieties.

MATERIALS AND METHODS

Porphyra tenera was obtained from Japan as the dried product ("Nori"). Specimens of the other marine Rhodophyta investigated were collected in the vicinity of La Jolla, California. *Porphyridium cruentum* (Pringsheim-Vischer strain) was cultured on Ketchum and Redfield's medium for marine diatoms (10). The blue–green algae studied included marine and fresh water species. They were harvested from laboratory cultures grown under white fluorescent lights at an intensity of approximately 100 ft.-candles.

With the exception of *P. tenera*, the algae (a few grams) were extracted in a fresh condition with distilled water in the cold and dark, and the colored extracts were chromatographed as quickly as possible. Algae which did not yield their pigment readily were ground with glass at 0°C. or frozen before extraction. The extracts were cleared by centrifugation at 4000 r.p.m., usually for 15 min., and chromatographed directly on tricalcium phosphate or aluminum hydroxide–Supercel columns, following the method of Swingle and Tiselius (8). The adsorbent was introduced as a slurry into glass columns, 8 or 20 mm. in diameter. It was continuously moistened and was packed by suction only, in order to allow rapid separation of the pigments. The column was washed with 1% NaCl before and after application of the colored extract, to which dilute saline was also added. Development was effected with phosphate buffers (0.0025–0.1 *M*; pH 6–6.5), the ease of pigment development varying with different species. The pigments were collected as eluates from the column.

Almost invariably, phycoerythrin preceded phycocyanin, which was more strongly adsorbed. Upon chromatography of most extracts, several phycoerythrins were observed as the buffer strength was increased; however, with the exception of phycoerythrin from the blue–green algae *Fremyella diplosiphon* and *Phormidium fragile*, such fractions displayed similar absorption spectra. In some chromatograms, a strongly adsorbed green zone was observed at the top of the column. This chlorophyll-containing fraction could not be eluted even with 0.1 *M* phosphate buffer. The appearance of a typical chromatogram of the fairly complex chromoprotein mixture of *Porphyra perforata* is shown in Fig. 1.

Spectrophotometric estimations of phycocyanin and phycoerythrin recovery from the column gave values of 50 and 75%, respectively. Chromatography does not seem to change the properties of the pigments; the absorption spectrum of crystalline phycoerythrin from *P. tenera*, prepared by fractional precipitation, was not altered by this treatment. The relative extinction values in the ultraviolet obtained for chromatographically separated phycoerythrin and phycocyanin compared favorably with values reported in the literature for recrystallized preparations (1), indicating effective separation from colorless protein impurities. When a colored fraction was not chromatographically homogeneous after one passage through the column, the eluate in question was dialyzed in the cold to remove the phosphate, and the impure pigment was rechromatographed.

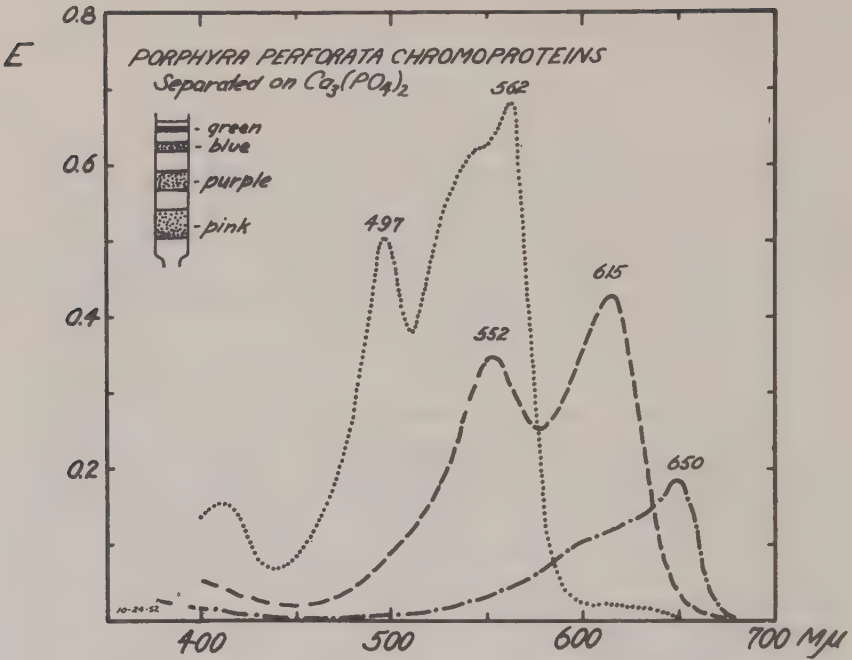

FIG. 1. Absorption spectra of *Porphyra perforata* chromoproteins from initial chromatogram, measured in phosphate buffer at pH 6–7.

· · ·· · variant of R-phycoerythrin
– – – – – R-phycocyanin
–· –· –· "allophycocyanin"

RESULTS AND DISCUSSION

The main types of bilichromoproteins which have been obtained, as well as typical sources, are listed in Table I.

a. C-phycocyanin

This pigment was found to occur in abundance in the blue-colored filaments of *Lyngbya lagerheimii* and was isolated in a high state of spectral purity (max. at 620 mμ) after passage through a single chromatographic column. Somewhat impure C-phycocyanin (max. at 612 mμ) was separated as a minor component of the pigment mixture present in the red filaments of *Phormidium fragile*. Kylin (11) reported only C-phycocyanin in this alga but we find two phycoerythrins present also (see below).

TABLE I

Spectral Absorption Maxima of Chromatographically Homogeneous Chromoproteins

R and C denote algal divisions Rhodophyta and Cyanophyta, respectively

Alga	Chromoprotein	Spectral absorption maxima mμ
Rhodymenia pacifica (R)	R-phycoerythrin	497, 537, 564
Porphyra perforata (R)	R-phycoerythrin variant	497, —, 562
Porphyridium cruentum (R)	*Porphyridium* phycoerythrin	—, 545, —
Phormidium ectocarpi (C)	Unnamed phycoerythrin	—, 542.5, 565
Phormidium persicinum (C)	C-phycoerythrin	—, —, 560
Porphyra perforata (R)	R-phycocyanin	—, —, 555, 617
Lyngbya lagerheimii (C)	C-phycocyanin	—, —, —, 620
Porphyridium cruentum (R)	Allophycocyanin?	—, —, —, —, 650

b. R-phycocyanin

The purple pigment of *Porphyra perforata* (see Fig. 1) was identified as R-phycocyanin. The corresponding zone from *P. tenera*, although blue-colored, was three-peaked (max. at 497, 565, and 612 mμ). It was obtained from several extractions of the available "Nori," and neither repeated chromatography nor fractional precipitation altered the spectrum. Both R-phycocyanin (1, 12) and C-phycocyanin (13) have been reported in *P. tenera.*

Porphyridium cruentum contains very little phycocyanin, and in order to separate it from phycoerythrin it was found necessary to add phosphate buffer directly to the extract before chromatography. This caused a fast migration of the phycoerythrin through the column, leaving a concentrated purple zone at the top. Residual phycoerythrin was eluted from the column with dilute buffer. At higher buffer strengths the purple and blue zones were moved off the column. The absorption curve of the former resembles R-phycocyanin, having maxima at 554 and 617 mμ. Some contamination of the purple pigment with phycoerythrin is not ruled out completely, since on rechromatography there was a slight reduction in the height of the absorption maximum at 554 mμ relative to that at 617 mμ. The ratio of extinction values for the purest preparation, 0.67, although low, falls within the range of values reported for R-phycocyanin (1, 7).

In a mixed chromatogram of *Porphyridium* "R-phycocyanin," and C-phycocyanin from *Lyngbya*, the two pigments were recovered as separate fractions, the C-phycocyanin being the more strongly adsorbed. Although there was considerable loss of pigment on the chromatogram, the observed behavior suggests that the "R-phycocyanin" is not a mixture of phycoerythrin and C-phycocyanin.

c. "Allophycocyanin"

The strongly adsorbed light-blue pigment from *P. perforata* having an absorption peak at *ca.* 650 mμ (Fig. 1) was also obtained chromatographically pure[4] from *P. tenera*, *Porphyridium cruentum*, *Fremyella diplosiphon*, and *Lyngbya lagerheimii*. There is no indication that this red-fluorescing proteinaceous pigment is a decay product of other chromoproteins; the curves of freshly prepared aqueous extracts of several algae, e.g., *Porphyra naiadum* (14), *P. perforata*, and *Rhodymenia pacifica* possess a "shoulder" at 650 mμ.

Molisch [cf. (3)] reported a blue–violet phycocyanin from *Oscillatoria limosa* with absorption bands at 530–575, 600–635, and 650–655 mμ. Boresch (15), however, did not find the far-red band. Lemberg and Bader (16) reported that they failed once to prepare C-phycocyanin from *P. tenera* despite previous and later successes. Instead, they obtained an amorphous blue protein having an absorption maximum at 655 mμ (no curve was given). The reason for the change in composition of the extract was not traced, but the assumption was made that this new pigment resulted from denaturation of the labile C-phycocyanin during extraction. It was named "allophycocyanin" and, from the small portion obtained free of phycoerythrin by repeated fractional precipitation, it was shown that the prosthetic group is phycobilin in nature.

The light-blue pigment which we have observed in both red and blue–green algae would appear to be allophycocyanin. Lemberg and Bader (16) obtained their pigment from dried *P. tenera*, which was subjected to prolonged extraction, and they assumed allophycocyanin to be an artifact. However, we obtained the "650 mμ" phycocyanin from fresh algae, extracted rapidly, as well as from dry *P. tenera* which had been extracted for several weeks.

The above findings suggest that allophycocyanin is a natural, although minor component of the chromoprotein mixture in several of the red and blue–green algae investigated.

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[4] The electrophoretic homogeneity of this pigment (from *P. naiadum*) at pH 5.15 has been established by Mr. R. Airth and Professor L. R. Blinks at the Hopkins Marine Station, Pacific Grove, California.

d. R-phycoerythrin

R-phycoerythrin from the higher red algae (subclass Florideae) *Rhodymenia pacifica* and *Polyneura latissima* displays three well-defined absorption maxima (Fig. 2). It was the only pigment observed on the column and migrated downward slowly as a single well-defined pink zone upon development with dilute phosphate buffer.

Phycoerythrin isolated from the lower red algae (subclass Bangiodeae) *Porphyra perforata* and *P. tenera* lacked a pronounced second peak; the absorption curve is similar to that reported for phycoerythrin from *Porphyra nereocystis* (14). *P. tenera* has previously been reported (1, 12, 13) to contain the classical three-peaked R-phycoerythrin. Apparently, this difference is not due to the method of extraction or to the chromatographic procedure. It is probable that the algal composition of commercial "Nori" is somewhat variable and it may be, as pointed out by Lemberg (17), that under different growth conditions, e.g., waters of different salinity, the same alga forms somewhat different chromoproteins.

e. Phycoerythrin ex Porphyridium

The phycoerythrin of *P. cruentum* was readily separated chromatographically from small amounts of more strongly adsorbed phycocyanin. Initially, the phycoerythrin formed a single zone on the column. Upon development with phosphate buffers of increasing strength, one major and several minor pink zones appeared, which in moving down the column overlapped the diffuse tails of preceding zones. This "tailing" [cf. (8)] was more pronounced in some extracts than in others. The individual phycoerythrins obtained in this way did not differ spectrally.

Porphyridium phycoerythrin has been identified variously by early workers (18, 15) as R- or C-phycoerythrin. We found phycoerythrin from *P. cruentum* to have a distinctly different spectrum from both of these pigments, when prepared under comparable conditions (Fig. 2; Table I). The chromatographically purified pigment displayed a broadened, single-peaked absorption curve in the visible spectral region, with a maximum at 545 mμ, a plateau extending from 550 to 557 mμ, and an inflection at *ca.* 500 mμ. Maxima were also observed at 368, 306, and 276 mμ in the ultraviolet. The shape of the absorption curve in the visible spectral region varied slightly in different preparations, but the

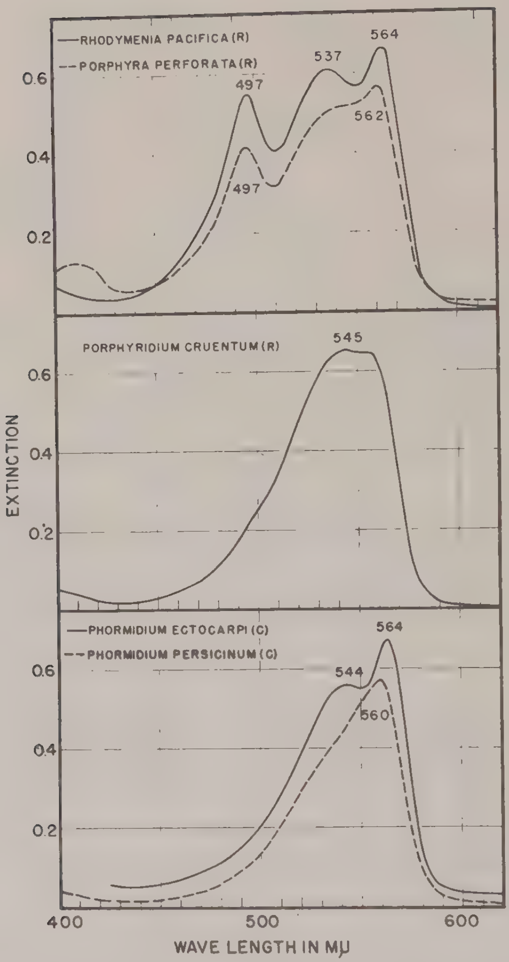

FIG. 2. Absorption spectra of various phycoerythrins, determined in phosphate buffer at pH 6–7. R and C denote representatives of the algal divisions Rhodophyta and Cyanophyta, respectively. Refer to Table I.

finding of a single-peaked spectrum is in agreement with some published curves (15, 19) and those obtained earlier[5] on phycoerythrin purified by fractional ammonium sulfate precipitation.

Koch (20) however, has recently reported that two strains of *P. cruentum*, including the Pringsheim-Vischer strain used in the present study, contained a three-peaked phycoerythrin with maxima at 495 (weak), 545, and 560–565 mμ. Oven-dried cells were extracted with 0.1 % Na_2CO_3, and spectral analyses were made on the unresolved aqueous extract. In checking Koch's procedure, we found no difference in the absorption spectra of *Porphyridium* extracts prepared by distilled water extraction of fresh cells and those which had previously been dried *in vacuo* at 48°C. The pH of 0.1 % (*ca.* 0.01 *M*) Na_2CO_3 was 10.4 and that of the final extracts was 8.6, or above. Further experiments were therefore conducted to determine the possible effects of extraction at different pH values on the absorption spectra of the whole extracts. Recently dried cells were extracted as follows (final pH of extracts given): 0.01 *M* acetate buffer at pH 5.5; 0.01 *M* phosphate buffers in the pH range 6.4–7.3; 0.01 *M* bicarbonate–carbonate buffers in the pH range 8.2–8.75 and 0.025 *M* bicarbonate–carbonate at pH 8.9. Selected absorption curves of the total extracts are given in Fig. 3.

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[5] Unpublished observations of F. T. Haxo and W. Silver, 1951.

Little difference was noted in the absorption curves in the pH range

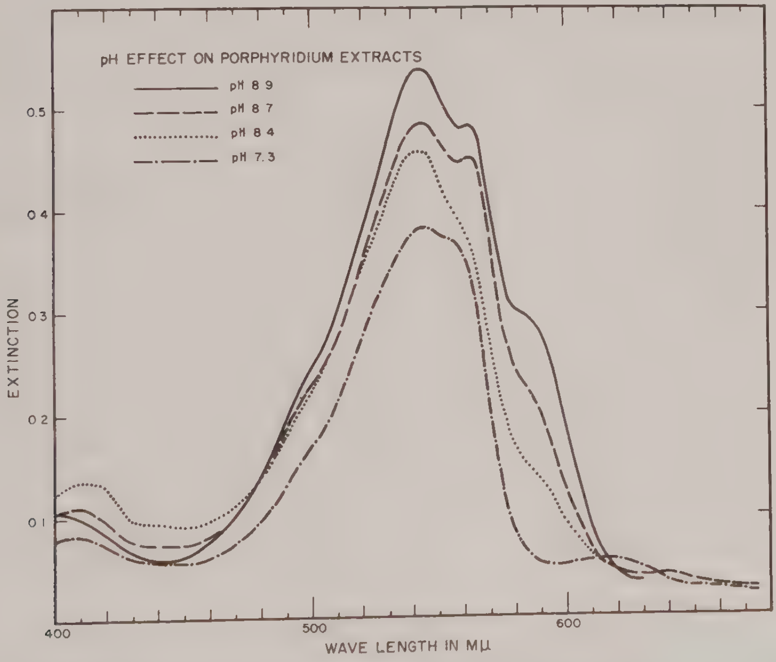

FIG. 3. Absorption spectra of unresolved *Porphyridium cruentum* chromoproteins, extracted at various pH values. The indicated pH is that of the final extract.

5.5–7.3; the phycoerythrin spectrum was typical of that found in the purified preparations described above. It would seem, however, that more alkaline conditions of extraction result in destruction of the phycocyanin and an alteration of the phycoerythrin spectrum. At pH values above 7.3 the 615-mμ maximum due to phycocyanin was absent, and the phycoerythrin spectrum showed a new maximum at 562.5 mμ and a "shoulder" at 580–585 mμ.[6] In some extracts a more marked inflection was present at *ca.* 500 mμ. The addition of Na_2CO_3 to distilled water extracts, with an associated large rise in pH, caused similar alterations in absorption spectra. In an extract brought from pH 8.6 to pH 5.9 by dialysis, there was a blunting of the 562.5-mμ peak and a disappearance of the 580–585-mμ inflection observed at the higher pH. This indicates that the spectral effect of extraction at high pH values is reversible to a certain extent. Chromatographic analysis of the dialyzate revealed the presence of both single-peaked (545 mμ) and two-peaked (545 and 562.5 mμ) phycoerythrin fractions, but no phycocyanin.

The correspondence noted by Koch between the 545 mμ and 560–565 mμ peaks of the carbonate-extracted phycoerythrin and that of the intact cell suspensions could be interpreted as evidence that the *Porphyridium* plastids are at an alkaline pH. However, contribution by phycocyanin to the absorption peak at 560–565 mμ in the intact cells cannot be overlooked. An alkaline plastid pH is difficult to reconcile with the observation that the phycocyanin content of *Porphyridium* cells is destroyed even under mild alkaline extraction. Furthermore, fresh cytoplasmic extracts of this alga are acid.

The absorption spectrum of intact *Porphyridium* cells has its closest parallel, as regards phycoerythrin, in the thallus absorption spectrum of *Porphyra naiadum* (14), although it reflects a smaller content of phycocyanin. Recent unpublished studies on *P. naiadum* var. *naiadum* (L. R. Blinks and R. Airth, personal communication) and *P. naiadum* var. *australis* (the present authors) have shown that purified phycoerythrin from these algae also differ spectrally from both R- and C-phycoerythrin.[7] Spectral differences have been observed in similarly prepared phycoerythrins from *P. naiadum* var. *australis* and *Porphyridium*. The question of their identity, however, remains unsettled.

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[6] Phycoerythrin was readily extracted from dried cells by the more alkaline buffers, leaving the cell residues green. Extraction under acidic conditions was much less effective.

[7] *Footnote added in proof.* This pigment, which may occur in several representatives of the Bangiales, has been tentatively designated B-phycoerythrin (Blinks, L. R., *in* "Autotrophic Micro-organisms," Fry, B. A. and Peel, J. L., Cambridge University Press, 1954).

f. C-phycoerythrin and Other Phycoerythrins of Blue–Green Algae

Conventional C-phycoerythrin (single sharp peak at 557–560 mμ) was observed only in blue–green algae: e.g., *Phormidium persicinum* (Fig. 2), *P. fragile*, and *Nostoc* sp. *Phormidium ectocarpi* contained as its only detectable bilichromoprotein an apparently new, two-peaked phycoerythrin, with maxima at 542.5 and 565 mμ (Fig. 2). *P. fragile* contained a somewhat similar two-peaked phycoerythrin (maxima at 542.5 and 565 mμ) as well as C-phycoerythrin and C-phycocyanin, listed in order of increasing adsorption affinity on tricalcium phosphate.

The results described for the last two mentioned algae are at variance with the earlier report of Kylin (11), who found only one absorption maximum (565 mμ) in *P. ectocarpi* extracts and only C-phycocyanin in *P. fragile* extracts. These discrepancies may well be due to the use of different algal strains. Chromatic adaptation of the algae under conditions of laboratory culture would be expected to alter only the quantitative and not the qualitative composition of the pigments (21). Artificial light did not cause *P. ectocarpi*, a red-colored marine Cyanophytum, to form phycocyanin, and this was also true of Kylin's culture.

In view of the apparent absence of phycocyanin in *P. ectocarpi*, a point which needs further confirmation, it is of interest that light absorbed by phycoerythrin is available for photosynthesis in this alga (22). This raises the possibility that phycocyanin, which has been demonstrated to function in the transfer of absorbed light energy from phycoerythrin to chlorophyll in red algae (19, 23) may not be essential for this transfer.

It is not known whether the spectral differences encountered in the unusual bilichromoproteins described above are to be attributed to chemical differences in the chromophoric groups or to different constituent proteins and chromophore–protein linkages. The present investigation does suggest, however, that the red and blue–green algae elaborate a greater diversity of such chromoproteins than has hitherto been suspected.

ACKNOWLEDGMENTS

We wish to thank Dr. Francis Drouet for identifying the blue–green algae, Dr. L. Provasoli for supplying the pure culture of *Phormidium persicinum* and directions for its cultivation, Professor E. G. Pringsheim for supplying the Vischer strain of *Porphyridium cruentum*, and Mr. H. Selby of the American Agar and Chemical Co., San Diego, California, for making available the *Porphyra tenera*.

SUMMARY

1. The chromatographic method of Swingle and Tiselius has been successfully applied to the separation and recovery of the bile pigment chromoproteins of a variety of red and blue–green algae.

2. In addition to the conventional R and C varieties of phycoerythrin and phycocyanin, several other chromoproteins were encountered. Representatives of both algal groups were found to contain, as a minor component, a blue proteinacious pigment, characterized by a single absorption maximum at 650 mμ. This chromoprotein is probably identical with Lemberg's allophycocyanin but is considered to be a natural constituent rather than an artifact formed during extraction. Unusual two-peaked phycoerythrins (maxima at 542.5 and 565 mμ) were found in extracts of the blue–green algae *Phormidium ectocarpi* and *Phormidium fragile*.

3. Phycoerythrin from the unicellular red alga *Porphyridium cruentum* was found to be distinct spectrally from both R- and C-phycoerythrin when all preparations were made at neutral or slightly acidic pH values. Under alkaline conditions of extraction (above pH 7.5), the phycocyanin content of *Porphyridium* cells is destroyed, and phycoerythrin with an altered spectrum is recovered. It is felt probable that *Porphyridium* phycoerythrin, isolated under the former conditions and characterized by a broadened single-peaked, instead of a sharp two- or three-peaked spectrum in the visible region, is the native pigment. The less abundant phycocyanin fraction of *Porphyridium* includes the "allophycocyanin" and a two-peaked pigment tentatively identified as R-phycocyanin.

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Deep-Sea Research, 1954, Vol. 2, pp. 107 to 121. Pergamon Press Ltd., London.
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Oscillations in sea temperature at Scripps and Oceanside Piers

ROBERT S. ARTHUR

Summary—Observations of sea temperature have been made in the vicinity of two southern California coastal piers some 40 km apart. Temperature-depth curves and temperature profiles show a shallow thermocline during the warm months. The depth of the thermocline varies with time, and, as a result, thermograms from fixed depths at the pier ends show oscillations. Changes of 5 C over a time interval of hours (Fig. 1) are frequent as the intersection of the thermocline with the sloping bottom moves inshore and offshore.

Thermograms from the two piers show no obvious coherence in the oscillations, but over a distance of 4 km along the Scripps shore there is evidence of coherence. Oscillations in the thermograms suggest the possibility of tidal periodicities but without the persistent regularity demonstrated for surface tides. An internal wave mechanism is consistent with the data. Internal waves have been confirmed in deeper water in the general area, and the oscillations can, therefore, represent the effect near the shore of internal waves of various periods, including tidal.

Applications to marine biology, underwater sound, and sedimentation are mentioned. It is suggested that coastal piers offer bases for economical operation of gauges which will help to determine the existence and nature of internal-tide waves.

INTRODUCTION

AT various times during the last 30 years records have been made of the temperature of water near the sea bottom and surface at the end of Scripps Pier, La Jolla, California (see Fig. 6 for location). Traces of temperature against time on the resulting thermograms show oscillations, and the records exhibit features characteristic of wide-band spectra with periods ranging from minutes to many hours. Prominent, even without smoothing, are " peaks " and " dips " separated by time intervals ranging from several hours to and including tidal intervals, and only these oscillations are considered in the ensuing discussion. The temperature of the water near the bottom may change by 5 C and, then, return to the original value some hours later. Variations of this magnitude occur only during the summer months when there exists near the surface a pronounced vertical gradient in temperature. A comparison of curves of temperature against depth as shown in Fig. 1 indicates the type of change discussed in the present paper.

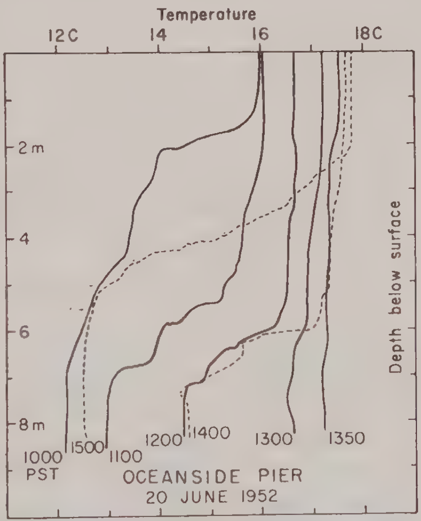

Fig. 1. Temperature-depth curves at indicated times (Pacific Standard) from BT lowerings at 140 m from pier end. Dashed curves reveal inflow of colder water at depth. LEIPPER (1950) shows a similar figure for Scripps Pier.

LEIPPER (1950) has made a detailed study of temperature records from the end of Scripps Pier and of bathythermograph (BT) records from the vicinity. He discusses a number of factors which may influence the sea-temperature variations in the Scripps area and emphasizes the importance of stirring of the stratified water and subsequent oscillating movements associated with tidal currents over an irregular bottom. HUBBS (1954) has floated a temperature-sensitive element and shown that the magnitude of the oscillations is very greatly reduced at the sea surface. DEFANT (1950b) has made a harmonic analysis of one of the thermograms presented by LEIPPER. He implies that the oscillations in the record are produced by internal waves of tidal period, which he designates more briefly as internal tides.

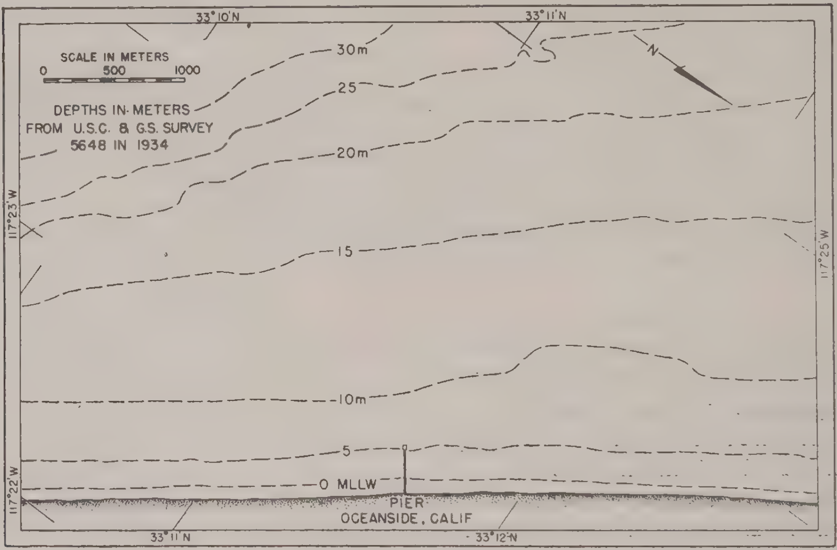

Fig. 2. Topography in Oceanside area. Since 1934 survey erosion has occurred along shore and depth increased along pier.

In the summer of 1952 several series of bathythermograms (Fig. 1) were obtained along the pier at Oceanside, California. Temperature oscillations of large amplitude were found in this location, where bottom topography is very regular in contrast to the Scripps area (compare Figs. 2 and 6). Beginning in June of 1953 thermographs were operated at both piers and additional observations were made in the vicinity of Scripps Pier. The extension of the observations in space makes possible a more complete description of the temperature variations.

A schematic model of the variations is presented first, and, then, data on which the model is based are given. Next, there follows a discussion of various features of the temperature oscillations and of factors which influence them. All observations have been made in shallow water, but it is likely that the phenomenon is related to deep-sea temperature changes as suggested by DEFANT.

A SCHEMATIC MODEL

Temperature Profiles. Isotherms in a vertical section normal to shore are shown at three different times in Fig. 3 (top row). The spacing of the isotherms exhibits a feature characteristic of summer conditions in the area. Below the sea surface there is a *thermocline layer* where the vertical temperature gradient is large relative to the gradient above and below. Within this layer, the surface which coincides with the maximum gradient is the *thermocline*.

The isotherms in the model section rise 5 m in 6 hrs and, afterwards, return to their original depths. As a consequence, the intersection of the thermocline with the sloping bottom moves towards shore and, then, away from shore. The sea level exhibits a tidal change of 1 m. No particular significance is to be attached to the phase coincidence in rise and fall of sea level and isotherms or the time interval of 12 hours, at least until actual data in a following section are examined.

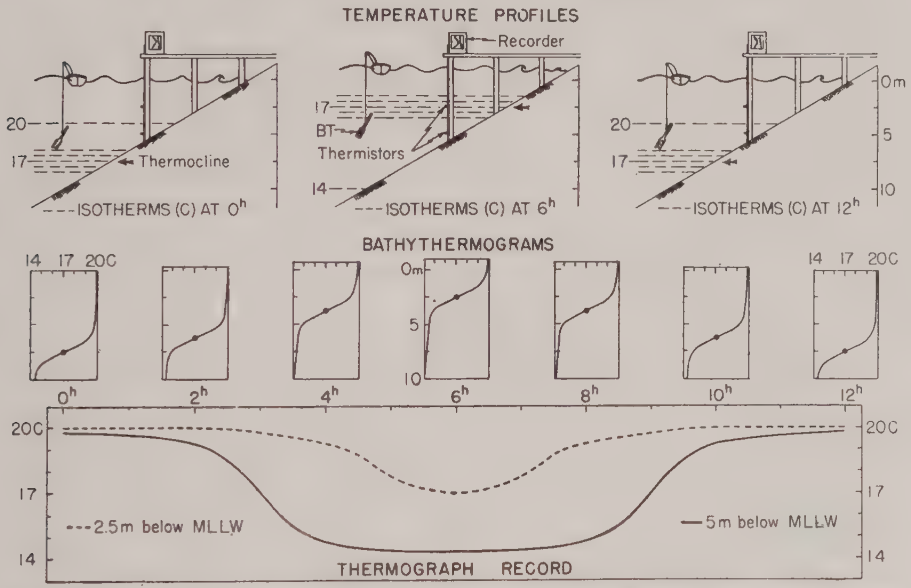
TEMPERATURE PROFILES
Recorder
20
17
Thermocline
---ISOTHERMS (C) AT 0^h
17
BT
Thermistors
14
---ISOTHERMS (C) AT 6^h
20
17
---ISOTHERMS (C) AT 12^h
0m
5
10
BATHYTHERMOGRAMS
14 17 20C
0m
5
10
14 17 20C
0^h
2^h
4^h
6^h
8^h
10^h
12^h
20C
17
14
---2.5m below MLLW
—5m below MLLW
THERMOGRAPH RECORD
20C
17
14

Fig. 3. Schematic model of temperature variation as shown by isotherms in profile normal to shore (top row), by BT traces from lowerings at fixed location at two-hour intervals (middle row), and by oscillation in thermograph traces from temperature-sensitive elements, e.g., *thermistors*, at fixed depths on pier pile (bottom row).

Bathythermograms. Lowering a BT produces a trace of temperature against pressure (depth), a bathythermogram. Suppose the vertical movement of the isotherms in the section is sinusoidal with respect to time. The vertical movement in the model is shown by a series of bathythermograms (Fig. 3, middle row) such as would be obtained by lowering a BT every two hours at the location indicated in the section. The depth of the thermocline is marked by a black dot on each trace and the dots lie on a sine curve under the assumptions made. The depth scale is fixed relative to mean lower low water (MLLW) rather than relative to the surface as on an actual BT grid.

Thermograph Record. A record of temperature against time such as would be obtained from temperature-sensitive elements, e.g., *thermistors*, mounted on a pier pile is also shown in Fig. 3 (bottom). The model thermogram indicates the temperature oscilations obtained from thermistors at two different depths as a result of the vertical movement of the isotherms. The shape of the temperature-time curves is of interest. It is clear that the slope of each curve depends upon both the vertical temperature gradient and the rate of vertical movement of the isotherms. Although the isotherms are assumed to move sinusoidally, the presence of a strong gradient in the thermocline layer causes marked deviation from the sinusoidal shape in the thermograph records. More than 75% of the temperature decrease or increase takes place within two hours.

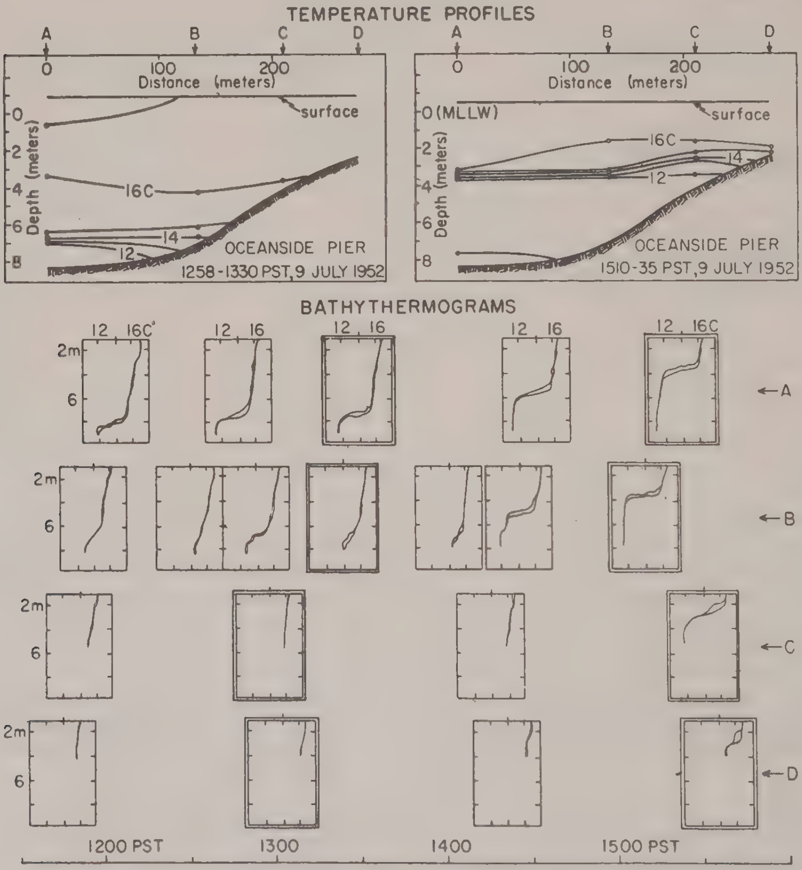

Fig. 4. Observed temperature variation along Oceanside Pier. Tracings of BT slides arranged vertically by station location A-D and centered horizontally according to time of lowering. Profiles at two different times constructed from tracings with double border. Surface level represents stage of tide.

A sufficiently steep temperature gradient in the thermocline layer, relative to the layers above and below, would produce thermogram curves of much greater distortion with the major part of the temperature change occurring in a fraction of an hour. The time at which the maximum change is recorded depends upon the depth of the thermistor and differs by more than an hour in the two model curves. The model has been simplified by assuming horizontal isotherms. If the isotherms are sloped and move horizontally as well as vertically, the shapes of temperature-time curves will be additionally affected. Time changes in the vertical temperature gradient will likewise affect the shapes of the curves.

OBSERVATIONS

The schematic model described above is oversimplified. However, it provides a useful framework for a description of variations in the temperature field as shown by observations. A brief description of instruments used and results obtained follows.

Instrumentation. The bathythermographs used had been modified to produce full travel of the smoked-glass slide at a depth of 15 m. The double traces which occur in some cases are believed to be the result of real changes in the temperature-depth curve. The slides were processed and photographic prints made by the standard method (LaFond, 1951).

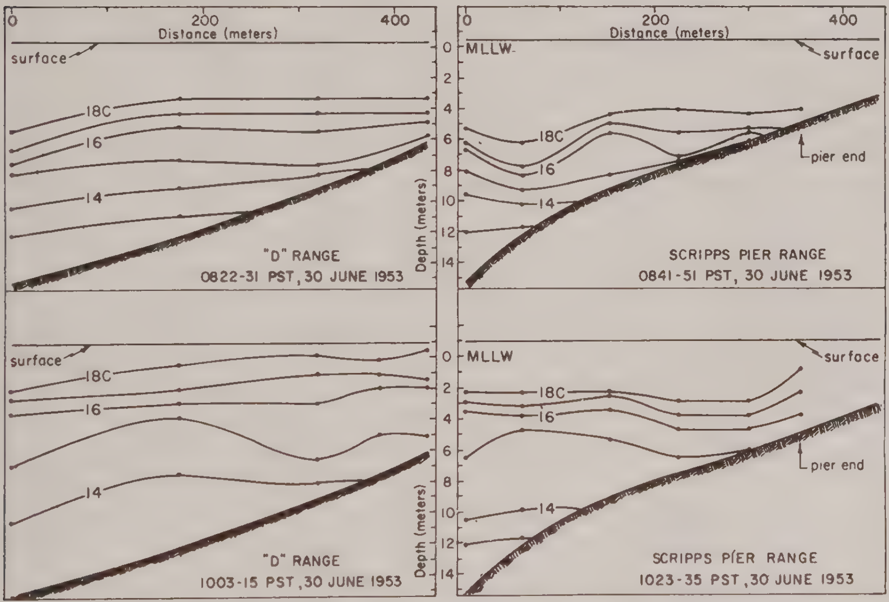

Fig. 5. Temperature profiles at two different times along two parallel ranges in Scripps area (range locations in Fig. 6). Plotted points from BT traces.

Electrical resistance thermometers with the temperature-sensitive elements mounted at the ends of water-tight conducting cables have also been employed. When these " casting " thermometers are used, the depth of the element is obtained by noting the length of cable paid out at the time of reading.

Continuous records of the temperature at two depths near the end of Scripps Pier and Oceanside Pier were made from thermistor elements. At La Jolla the thermistors were mounted on a pier pile at depths of 1·3 m and 4·5 m below MLLW and at Oceanside at depths of 1·5 m and 5·3 m. The lower thermistor was within 1 m of the bottom at La Jolla and about 3 m above bottom at Oceanside. Each

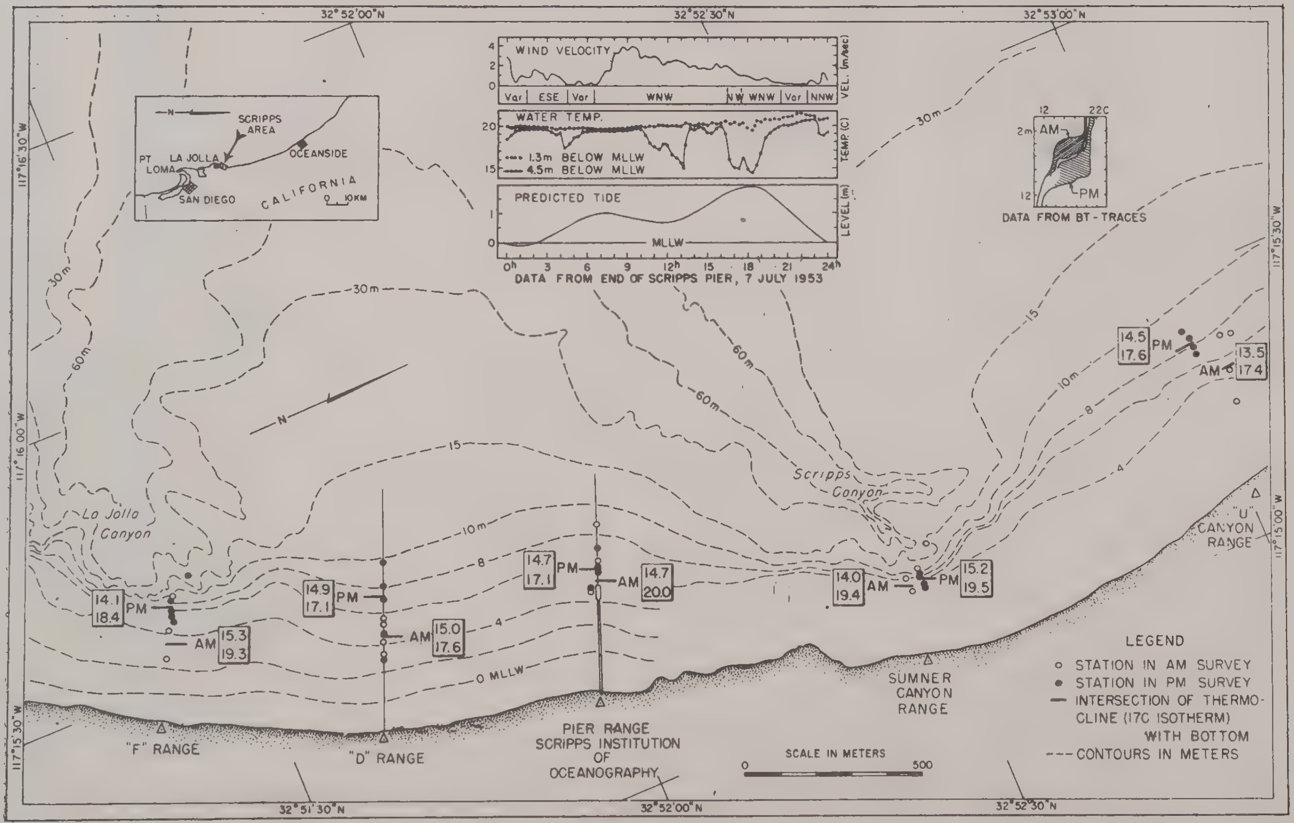
32° 52'00"N
32° 52'30"N
32° 53'00"N
32° 51'30"N
32° 52'00"N
32° 52'30"N
117° 16'30"W
117° 16'00"W
117° 15'30"W
117° 15'30"W
117° 15'00"W
N
SCRIPPS AREA
PT LOMA
LA JOLLA
OCEANSIDE
SAN DIEGO
CALIFORNIA
0 10KM
WIND VELOCITY
VEL. (m/sec)
4
2
0
Var
ESE
Var
WNW
NW
WNW
Var
NNW
WATER TEMP.
TEMP. (C)
20
15
1.3m BELOW MLLW
4.5m BELOW MLLW
PREDICTED TIDE
LEVEL (m)
1
0
MLLW
0h
3
6
9
12h
15
18
21
24h
DATA FROM END OF SCRIPPS PIER, 7 JULY 1953
12
22C
2m
AM
PM
12
DATA FROM BT-TRACES
30m
60m
15
10m
8
4
0 MLLW
La Jolla Canyon
Scripps Canyon
N
14.1
18.4
PM
AM
15.3
19.3
14.9
17.1
PM
AM
15.0
17.6
14.7
17.1
PM
AM
14.7
20.0
14.0
19.4
AM
PM
15.2
19.5
14.5
17.6
PM
AM
13.5
17.4
"F" RANGE
"D" RANGE
PIER RANGE
SCRIPPS INSTITUTION OF OCEANOGRAPHY
SUMNER CANYON RANGE
"U" CANYON RANGE
SCALE IN METERS
0
500
LEGEND
STATION IN AM SURVEY
STATION IN PM SURVEY
INTERSECTION OF THERMOCLINE (17C ISOTHERM) WITH BOTTOM
CONTOURS IN METERS

Fig. 6. Location of intersection of thermocline with bottom in Scripps area in AM (0932-1103PST) and PM (1338-1507PST) surveys on 7 July 1953. Numbers in boxes show temperature (C) of bottom water at stations immediately seaward and shoreward of intersection. Insets: location map (left); wind, water temperature, and tide at pier end (center); comparison of BT-grid areas covered by AM and PM traces (right).

of the two signals at La Jolla was fed into a separate channel of a 12-channel Speedomax (*Leeds and Northrup Co.*) and was printed every 38·7 sec ; the Speedomax used at Oceanside was a single-channel, pen-type and the signal from the upper thermistor was programmed to record for ten minutes out of each hour.

For the purposes of the present study it is sufficient to know the temperature to an accuracy of ± 0·2 C and all instruments were so calibrated. Except for one of the casting thermometers, the instruments are capable of greater accuracy and differences between readings may be trusted to within ± 0·1 C.

Temperature Profiles. BT lowerings were made at four positions along Oceanside Pier, and depths of whole number values of temperature were read from the right-hand traces of the resulting bathythermograms. Fig. 4 shows the isotherms interpolated between the four positions for two sets of observations. About one-half hour was required to make each set of lowerings and the time interval between profiles is between two and three hours. BT lowerings were made on two other days, and results were similar, i.e., vertical movement of isotherms was noted.

Fig. 5 shows temperature profiles along the Pier Range and " D " Range, Scripps area (Fig. 6 shows range locations). The time separation is about two hours, and around ten minutes were required to make the BT lowerings and run each range with the amphibious craft (DUKW). Positions along the range were determined by sextant angles. Additional profiles were made on two other days along the ranges and on three different days along Scripps Pier itself. Results were similar to those presented.

Intersection of the Thermocline with the Bottom. The inshore-offshore movement of the intersection of the thermocline with the bottom was determined in the Scripps area along a section of shore between 3 and 4 km long. Stations along or in the vicinity of five different ranges (Fig. 6) were occupied by the DUKW, and the temperature of the water immediately above the bottom was measured with a casting thermometer. As before, positions were determined by sextant angles, and the depths were noted as an added check on position and inshore-offshore movement between the morning (0932-1103 PST) and afternoon (1338-1507 PST) surveys. The 17 C isotherm was taken to represent the thermocline and its intersection was interpolated between the observed values of bottom temperature. The change in thermal structure is indicated by an inset in Fig. 6 which shows the BT-grid areas encompassing all morning (AM) and all afternoon (PM) traces from a total of 16 bathythermograms taken during the two surveys.

For reference, information is presented from records of wind and temperature near the end of Scripps Pier. Values of wind velocity and of temperature have been read at 20-min intervals and connected by a smooth curve (Fig. 6, inset). The dominant wind direction is included and also the predicted tide (U.S. Coast and Geodetic Survey, 1952). In general, observed tide level is within 10 cm of the predicted value at Scripps Pier.

Thermograms, Wind and Tide. Values of temperature on the hour and half-hour have been read for an eight-day period from records from three of the four thermistors. Only hourly readings could be made from the programmed thermogram for the 1·5 m depth at Oceanside. The successive values, which were read to the nearest quarter degree centigrade, were plotted and joined by straight lines (Fig. 7). This procedure is necessary to condense the thermograms so that comparisons and

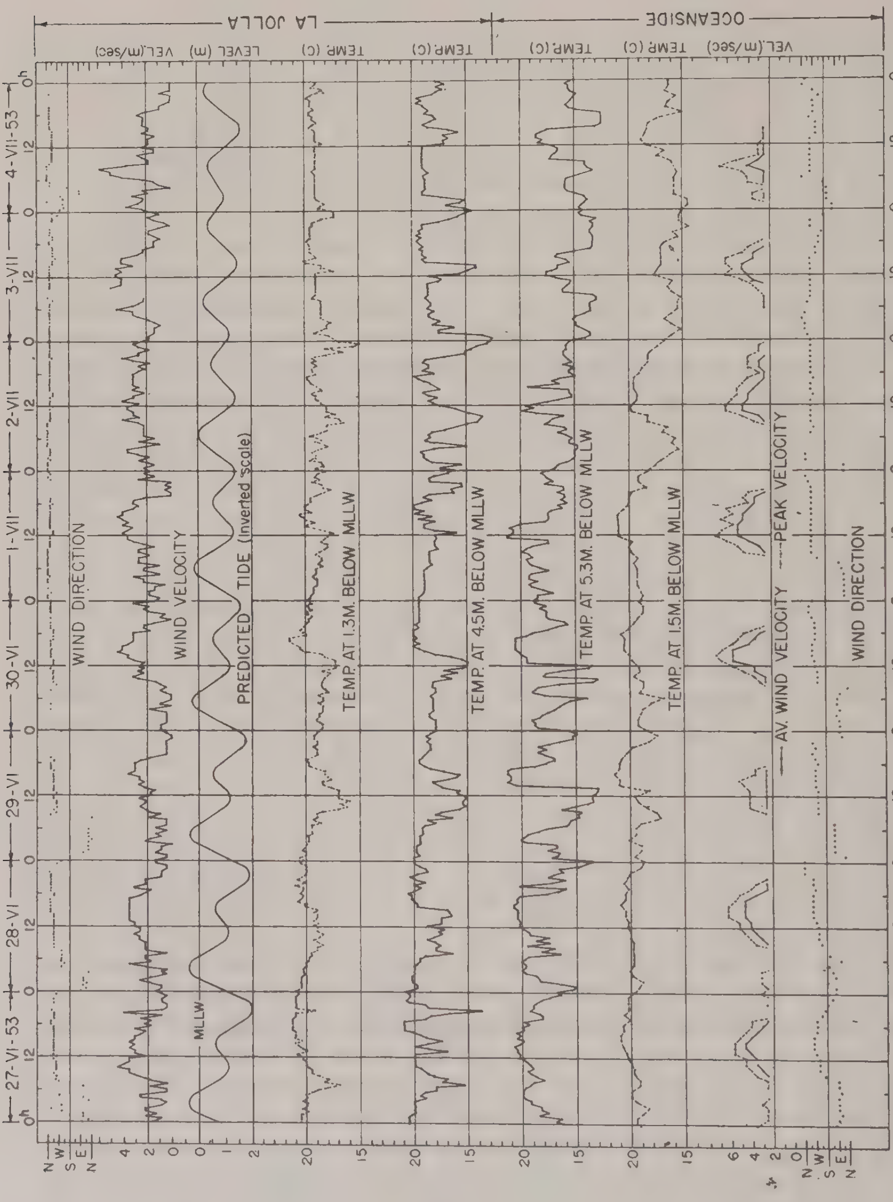

Fig. 7. Smooth temperature oscillations at two depths from pier ends at La Jolla and Oceanside, California, from 27 June through 4 July 1953. Variation in wind and tide also shown for comparison.

reproductions may be made. The degree of smoothing for an extreme case may be judged from examination of a tracing of the Oceanside thermogram for a six-hour period on 30 June 1953 (Fig. 8).

Oscillations in temperature as large as those shown in Fig. 7 have occurred during some periods in the summer and fall of 1953. The six-hour interval in Fig. 8 was specifically chosen because it represents an extreme in the magnitude of shorter-time fluctuations during the whole eight days.

For comparison with temperature, the wind and tide are also shown on Fig. 7. Wind records from a Friez Aerovane at the end of Scripps Pier have been read at half-hour intervals. The direction from which the wind blew was read to the nearest of 16 points of the compass when the velocity was greater than 1 m/sec. The predicted tide for Scripps Pier is shown on an inverted scale and the same curve applies to Oceanside. Wind data for Oceanside are taken from records at the Camp Pendleton boat basin, 3 km north of the Oceanside Pier. Hourly averages and peak velocities above 2·5 m/sec have been plotted along with direction to the nearest of 16 compass points.

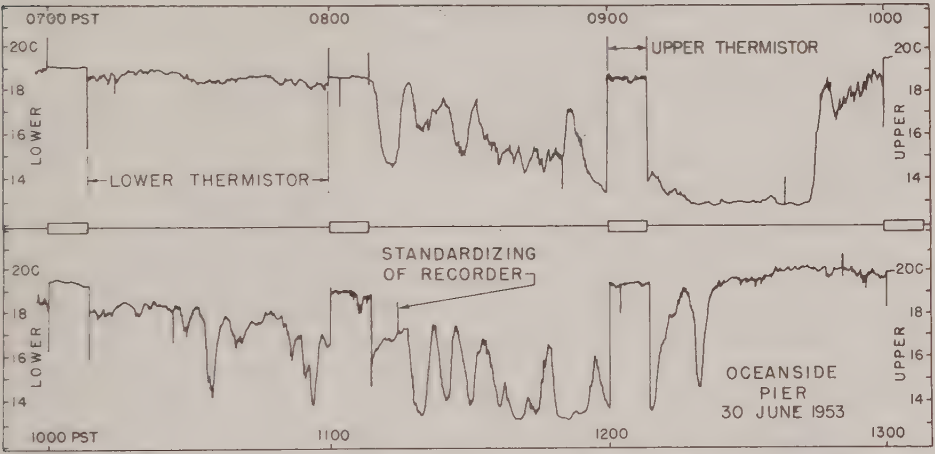

Fig. 8. Reduced tracing of programmed thermogram from Oceanside Pier for 0700-1300, 30 June 1953. Boxes on centerline of diagram indicate first 10 min of each hour when trace is from upper thermistor (1·5 m below MLLW). Remainder of time trace is from lower thermistor (5·3 m below MLLW). Temperature scales differ slightly because of non-linearity of thermistors. Sharp, vertical lines in trace are caused by programming and standardizing mechanisms.

DISCUSSION

The Nature of the Temperature Oscillations. The model involves the simple and obvious proposition that oscillations in the thermogram traces are associated with vertical movement of isothermal surfaces. The reproduced data, particularly the profiles, support the proposal. Additional profiles, not reproduced, are in agreement.

However, as previously stated, the shape of the thermogram curves depends not only upon the rate of rise or fall of isotherms but also upon their vertical spacing. Fig. 7 shows that traces from thermistors at different depths exhibit differences in amount and rate of temperature change. Temperature changes from thermistors near the surface are often small relative to changes from thermistors near the thermocline.

Local temperature changes may be caused by local heating or cooling or by horizontal and vertical water movement. As LEIPPER (1950) has pointed out, gain or loss of heat through the surface cannot account for the temperature oscillations recorded from deeper thermistors. A day-night range of less than 2 C in the upper few meters is the most that can be expected. The observed oscillations must be accompanied by water movement and, consequently, the proposed model is incomplete dynamically. With regard to water movement, an examination of the data shows first that the isotherms are not simply following the rise and fall of the sea surface under the influence of ordinary tides. Secondly, the profiles show that different isotherms may have differing magnitudes of rise or fall. The 13 C and 14 C isotherms on the Pier Range profile in Fig. 5 show much less change than other isotherms. It is concluded that the water movement *may* vary with depth.

As proposed in the model, the profiles and Fig. 6 indicate that the intersection of the thermocline with the sloping bottom does move toward or away from shore. The observed isotherms are not everywhere horizontal but show appreciable slope both normal and parallel to shore.

The observations reproduced are confined to an area between the surf zone and the 15 m contour. At any instant, the surf zone is generally well stirred and isothermal, but it experiences temperature variations similar to those of water near the surface at the pier ends. There is evidence that temperature oscillations extend far seaward of the reproduced sections. Unpublished bathythermograms taken by HUBBS and others to a distance of 2 km from shore in the Scripps area show pronounced vertical movement of isotherms at all stations during a time interval of more than 24 hr. LEIPPER (1950) comments on the variation in depth of the thermocline observed on 15-16 September 1948 at Scripps Pier and at two ships located approximately 33 km west-northwest and northwest of the Scripps Pier, respectively. Profiles reported by RAWN, *et al.* (1952) from the Oceanside area show that the oscillations extended at least 4 km from shore in that area during one 24-hr interval. Profiles off Point Loma (RAWN, *et al.*, 1952) and temperature variations recorded by UFFORD (1947) show the phenomenon extending south of La Jolla.

The profiles and thermograms show that the temperature oscillations at Scripps and Oceanside have a similar character in spite of the great difference in bottom topography. There is no obvious, persistent coherence in the thermograms from these two locations over 40 km apart (Fig. 7). On the other hand, there is evidence of coherence on one occasion over a distance of less than 4 km (Fig. 6).

Periodicities. A description of the thermogram data is incomplete without mention of periodicities. Rhythmic phenomena which might produce oscillations in temperature are the diurnal wind and the tides. The wind has the character of a land and sea breeze and the tides are of the mixed type, showing considerable diurnal inequality (Figs. 6 and 7).

The thermogram curves have a rather high degree of irregularity in general appearance. However, if curves of wind and temperature or tide and temperature and compared (Fig. 7), one gets the impression that good correlation exists *in some sections of the records.* Good correlation in a particular interval of time may result from chance as COLE (1951) has so convincingly demonstrated in a comparison of curves derived from Douglas fir growth and random sampling numbers from Tippet.

As LEIPPER states the temperature dips may be associated with any stage of the tide. However, he reports that of the total number of distinct dips occurring in several hundred days 55 per cent came within two hours of high tide while only 24 per cent came within two hours of low tide. DEFANT (1950b) has subjected a four-day thermograph recording from Scripps Pier to harmonic analysis and concludes (p. 125) :

> " The tidal influence is very pronounced. The tide and temperature curves are almost completely reversed, and the phase differs by half a period. The variation in temperature with semidiurnal tide in the surface and bottom layers attains an amplitude [double] of more than 3°C ; with the diurnal wave in the surface layer it attains a magnitude of only 1°C."

DEFANT (1950a, b) has suggested that internal waves of tidal period, i.e., internal tides, are widespread in the oceans and he includes the above analysis as part of the evidence. There remains a question of significance (HAURWITZ, 1952) and the length of record examined is important. In the Scripps thermogram for 4·5 m (Fig. 7) the correlation between inverted tide and temperature is obviously good on July 3 and 4, as it was in the record analyzed by DEFANT. However, there is not such an obvious correlation on the other six days. It is, therefore, concluded that while thermograms suggest the possibility of oscillations of tidal period, the oscillations in no way show the persistent regularity demonstrated for surface tides.

Isotherms in the sea may have a vertical oscillation of tidal period which is more persistent than shown by the thermograms. The amplitudes of trace oscillations depend critically upon the relative depth of thermistor and thermocline. Since the mean depth of thermocline may change after several days, the interpretation of a long thermogram is difficult. Data on the actual vertical movements of isotherms are needed and could be obtained by programmed recordings from thermistors closely spaced along a vertical cable. It is hoped that several such internal-tide gauges can be operated from the ends of piers in the future. Since temperature " noise " is present, some filtering of the records will undoubtedly be desirable and, then, analyses for periodicities and significance tests can be made.

Internal Waves. Temperature oscillations of the type shown by the data, but from observations in deeper water, have been attributed to internal waves and internal tide (e.g., see SVERDRUP, JOHNSON and FLEMING, 1942 and LAFOND, 1949). An internal-wave mechanism is in complete agreement with profiles and other data from Oceanside as well as Scripps. However, observations of the motion are necessary to confirm the presence of internal waves and these have not been made.

UFFORD (1947) has demonstrated the existence of internal waves of periods from 9 to 136 minutes in the San Diego area and has remarked on the existence of waves of tidal period which show prominently in his temperature data. EWING (1950) has shown a relationship between band slicks on the surface and refracted internal waves in the San Diego and La Jolla areas, and both he and UFFORD find internal waves which progress toward shore.

Since many oscillations in the thermogram traces quite possibly result from internal waves, speculation on the behaviour of internal waves in shallow water may be of interest. In addition to refraction, shoaling water may cause reflection and possibly standing waves, or internal breaking and surf (DEFANT, 1950a) may result. From KEULEGAN'S (1953) theoretical investigation of internal solitary waves one might expect that internal troughs as well as internal crests could reach instability and break in shoaling water.

Measurements of temperature with depth have occasionally shown inversions which would be expected with internal surf. Pertinent in this regard are observations of a narrow zone of debris, kelp, foam, and jellyfish with associated band slicks which approached Scripps Pier on 12 June 1953. The debris zone extended generally parallel to shore but was curved inward toward shore over both submarine canyons. The temperature at the pier end was 17·1 C at surface and 12·7 C at bottom with the thermocline located at 2 to 3 m below surface. As the debris zone approached the pier end the thermocline moved downward and within 15 min after the zone had passed the pier end the bottom temperature was 16·8 C. However, water 3 m above bottom was 0·3 C colder than water at the bottom. The tide was ebbing during the observations and the wind record was very similar to that of 30 June 1953 (Fig. 7).

The observed movement of the debris zone may indicate a shoreward movement of warm surface water accompanied by convergence and sinking. Continuity requires a corresponding seaward movement of deeper, cold water. Temperature observations are consistent with such an interpretation of the motion and suggest the approach toward shore of a steep, or breaking, leading edge of an internal trough. The orientation of debris zone and slicks indicates refraction by the canyons.

The velocity of an internal solitary trough is 15 cm/sec if calculated from Keulegan's formula (1953, eq. 88) for a two-layer system with upper layer of thickness 3 m, lower layer 5 m, density difference of 0·001 gm/cm^3, and trough with height 2 m. On the basis of visual estimates of distances at various times, the observed speed of the debris zone was about 10 cm/sec. The water velocity should be less than or equal to the internal trough velocity. However, both estimates are very approximate, and a comparison simply shows that the observations *may* indicate an internal wave mechanism.

If the temperature oscillations are associated with internal waves, the problem of the cause of the waves still remains. Tide (DEFANT, 1950a ; HAURWITZ, 1950) and wind are probably important, but the data as presently analyzed offer little more than a basis for speculation. RUDNICK and COCHRANE (1951) suggest that the generation of internal tide at ocean boundaries seems a very probable process. In this regard, the thermograms show that there may not be a constant phase coupling between internal and surface tides in very shallow water.

Advection and Stirring. LEIPPER (1950) proposes as an explanation that temperature variations at Scripps Pier may be caused by stirring of shallow stratified water and subsequent oscillating movements associated with tidal currents. He suggests that the irregular bottom topography causes horizontal differences in tidal current in certain regions. The differences, in turn, lead to the formation of eddies which bring about stirring and cooling in the surface layers. Oscillating tidal currents then cause the " cold spot " so formed to migrate back and forth.

The relatively regular topography in the Oceanside area (Fig. 2) makes it unlikely that differential tidal stirring exists there on a scale comparable to that suggested by LEIPPER for the Scripps area. Different explanations may be required for the two areas, but the similarity in observed temperature oscillations make a common explanation such as an internal-wave mechanism attractive.

However, the present data do not rule out the possibility of advection and stirring being factors in producing oscillations. For example, if the isothermal surfaces are for any reason sloped in a direction parallel to shore and there is a current component parallel to shore, temperature variations will be recorded at a fixed locality. Some stirring must accompany internal waves, particularly in shallow water. Coastal currents, wind stirring, and surf stirring are perhaps all factors which affect the very shallow summer thermocline in the nearshore region. Time and space variations in these factors exist and may certainly cause some temperature variation.

Advection and stirring associated with transient rip currents have been observed to produce temperature variations of as much as 1 C or 2 C at the end of Scripps Pier.

It is, of course, well established that advection and stirring by winds produce longer-term changes in temperature, e.g., as a result of upwelling (SVERDRUP, JOHNSON, and FLEMING, 1942) or sinking (LONGARD and BANKS, 1952).

Applications. The temperature oscillations represent changes in the nearshore environment which are of interest in marine biology. Benthic forms at depths ranging from about 3 m to at least 8 m may experience abrupt changes in temperature during a single summer day which are as great as the seasonal changes. The 0800 temperature of bottom water at Scripps Pier for the coldest month, February, averaged over the years 1925-1951, is 13·8 C and for the warmest month, August, 18·8 C. This seasonal change of 5 C was equalled on four out of the eight days from 27 June to 4 July 1953 (Fig. 7), and at four different times the temperature near the bottom dropped to 14 C or lower. Such changes are frequent rather than rare. Even in August the temperature dips reach 15 C or lower.

The vertical movement of isotherms causes changes in the thickness of the isothermal layer above the thermocline. The changes extend out 2 km or more from shore. Refraction of horizontally propagated underwater sound, which is critically dependent upon the temperature field, will be affected by the observed changes. In this area salinity changes are small enough to be ignored in comparison with temperature changes in calculating sound velocity. The temperature oscillations are associated with density oscillations of importance.

Horizontal and vertical movements of water are associated with the temperature oscillations. At least in part the horizontal movement is onshore and offshore, probably in the nature of an internal wave. Estimates show velocities greater than the onshore-offshore movement from surface tide. This motion should be considered in work on movement of suspended sediment.

Some vertical stirring and mixing undoubtedly accompanies the oscillations. If internal waves become unstable and break, the stirring may appreciably reduce the nearshore temperature in the sense described by COOPER (1947).

The observations suggest the existence of internal tide, but more suitable data are needed for analysis. Piers on exposed coasts constitute a bridge over the surf zone and are more economical bases for long-term operation of internal-tide gauges than anchored ships. It is suggested that such facilities be exploited more. Undoubtedly, comparisons with at least limited observations from deep anchor stations will be desirable and necessary to establish fully the nature of internal tide.

ACKNOWLEDGMENTS

J. M. SNODGRASS and F. E. SNODGRASS and their assistants have designed, installed, and maintained the electrical thermometers and thermographs essential to the observational programme. E. STRONG and H. BLAIR have assisted with observations and records. Wind data from Camp Pendleton have been furnished by the Surf and Weather Station, Marine Corps Base.

C. L. HUBBS, J. D. COCHRANE, P. L. HORRER and J. L. REID have generously allowed me to examine detailed observations of temperature and current made by them in the La Jolla area over a two-day period. A. J. CARSOLA, of the Navy Electronics Laboratory, has shown me records of temperature in the San Diego area which have oscillations similar to those reproduced.

My interest in the problem arose through discussions with C. L. HUBBS, D. F. LEIPPER, now of the Agricultural and Mechanical College of Texas and B. K. COUPER, now of the U.S. Navy Bureau of Ships, who made extensive investigations of sea-temperature variations in the local coastal area. I acknowledge with pleasure the many helpful suggestions received from them and others.

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Contribution from the Scripps Institution of Oceanography, New Series No. 748. This work represents results of research carried out for the Office of Naval Research and Bureau of Ships, U.S. Navy, and the U.S. Army Beach Erosion Board under contracts with the University of California.

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Printed in Great Britain by The Salisbury Press Ltd., Publicity House, Wilton Road, Salisbury, Wilts. (88344)

DEEP-SEA CHANNELS, TOPOGRAPHY AND SEDIMENTATION

BY

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Reprinted for private circulation from
The Bulletin of the American Association of Petroleum Geologists
Vol. 39, No. 2, February, 1955

(125)

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BULLETIN OF THE AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS
VOL. 39, NO. 2 (FEBRUARY, 1955), PP. 236-255, 7 FIGS.

DEEP-SEA CHANNELS, TOPOGRAPHY, AND SEDIMENTATION[1]

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ABSTRACT

The type and distribution of much of the minor topography in the northeastern Pacific basin can be correlated with the accessibility of a given area to deposition from turbidity currents. Deep-sea areas separated from North America by basins or troughs, which act as sediment traps for turbidity currents, are characterized by a highly irregular relief of a few hundred feet. Other areas connected to the continent by a gradual continuous slope are characterized by very smooth plains like those of the North Atlantic sea floor. These plains slope out from the continent except in the vicinity of long ridges on the sea floor. The plains slope around the ridges because the slopes are formed by turbidity currents and the ridges act as dams to deflect the currents to one side. Rough-bottomed basins thousands of feet deep are found in the regions of smooth plains, but with one exception all are inaccessible to turbidity currents because they are surrounded by mountains, or lie on the "lee" side of ridges relative to the general direction of flow of turbidity currents. The exceptional basin is in a seismically active area, and it may have formed too recently to be filled by turbidity-current deposition.

Turbidity currents have formed deep-sea fans at the mouths of many submarine canyons, and deep-sea channels cross most, if not all, of the fans. All twelve of the channels which have been explored in any detail hook sharply to the left across the fans. This left hook can be explained as a secondary effect of the action of Coriolis force on the turbidity currents which formed the channels. Without channels, this type of flow would have no tendency to hook left. Unchannelized turbidity currents are required to form the fans.

INTRODUCTION

Sediment deposited by turbidity currents is increasingly identified in the geological column (Kuenen and Migliorini, 1950; Natland and Kuenen, 1951; Kuenen and Carozzi, 1953) and on the deep sea floor (Bramlette and Bradley, 1940; Ericson, Ewing, and Heezen, 1951; Phleger, 1951; Shepard, 1951). It appears that in some environments turbidity currents may be the dominant agents transporting and depositing sediment. The present study is concerned with the topography of the sea floor which, quite independently of sediment sampling, gives another type of evidence by which to determine the existence of turbidity currents and to judge their importance relative to other agents of sedimentation in the deep sea.

Such significant features as deep-sea channels can rarely be recognized without echograms which, consequently, are all-important to understanding deep-sea topography. Echograms showing more than 120,000 miles of the Pacific sea floor have been collected by various expeditions and cruises of the Scripps Institution of Oceanography and the Navy Electronics Laboratory and have been examined as a part of the present study. Several cruises, notably in 1949 off San Diego, in 1951 off Monterey Submarine Canyon, and in 1952 off Oregon and Washington, were specifically designed to investigate deep-sea channels and related topography.

Additional evidence has also been derived from the detailed sounding lines and echograms made by the Coast and Geodetic Survey in the northeastern Pacific, particularly the Gulf of Alaska. Because of their planned spacing and large number, these soundings permit contouring the sea floor in far greater detail than would otherwise be justified.

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[1] Navy Electronics Laboratory Professional Contribution No. 34. Scripps Institution of Oceanography Contribution No. 750. Manuscript received, September 28, 1954.

[2] Navy Electronics Laboratory.

Many of the ideas presented here have occurred almost simultaneously to several geologists as they have watched, sometimes together, an echo sounder draw a profile of the sea floor. After several years of development, it is virtually impossible to assign all credits exactly where they are due, and it is not even clear in which ocean some ideas originated. Under the circumstances, the writer prefers to acknowledge his indebtedness to the spirit of cooperation which has resulted in the rapid advances in oceanography, rather than to attempt to acknowledge individuals.

As to the manuscript, Gustaf Arrhenius, M. N. Bramlette, Robert S. Dietz, and Edwin L. Hamilton have been kind enough to read it and suggest improvements.

TOPOGRAPHY EXPECTED FROM VARIOUS TYPES OF SEDIMENTATION

Two general processes may be considered as spreading sediment from the continents into the deep sea: suspension in the main volume of the ocean, and mass movements in the form of turbidity currents and slumps. The depositional topography produced by these processes may be similar under some conditions. Consider an area where the initial relief consists of a steep continental slope bordering a gently sloping or level deep-sea floor (Fig. 1). Turbidity currents flowing down the slope would be slowed on the deep-sea floor and would also gradually build an apron of coalescing deep-sea fans. A sedimentary wedge resembling coalescing deep-sea fans would be produced by deposition from volume suspension which would decrease outward from the continental margins. The sea floor off eastern North America has the form of a steep continental slope separated from a relatively flat sea floor by a sloping transition area. For this reason the gross topography can not be used to indicate the dominant type of sedimentation in the area.

In different conditions the topography produced by different processes of sedimentation may be distinctive and may clearly identify the process. For example, an area may be selected, where the sea floor has a large initial relief of trenches, troughs, seamounts, and ridges. Material in volume suspension spreads outward from the continent without regard for the relief and forms a sedimentary wedge sloping toward the deep sea (Fig. 1). Turbidity currents, however, can not rise from deep trenches or surmount high ridges; therefore, they deposit no sediment on the oceanic side of the topography (Fig. 1). As deposition continues, the initial relief would be covered and once again the topography of the sea floor would give little indication of the dominant type of sedimentation. The topography of the sea floor off western North America features major relief. It will be shown how great is the effect of this topography on deep-sea sedimentation.

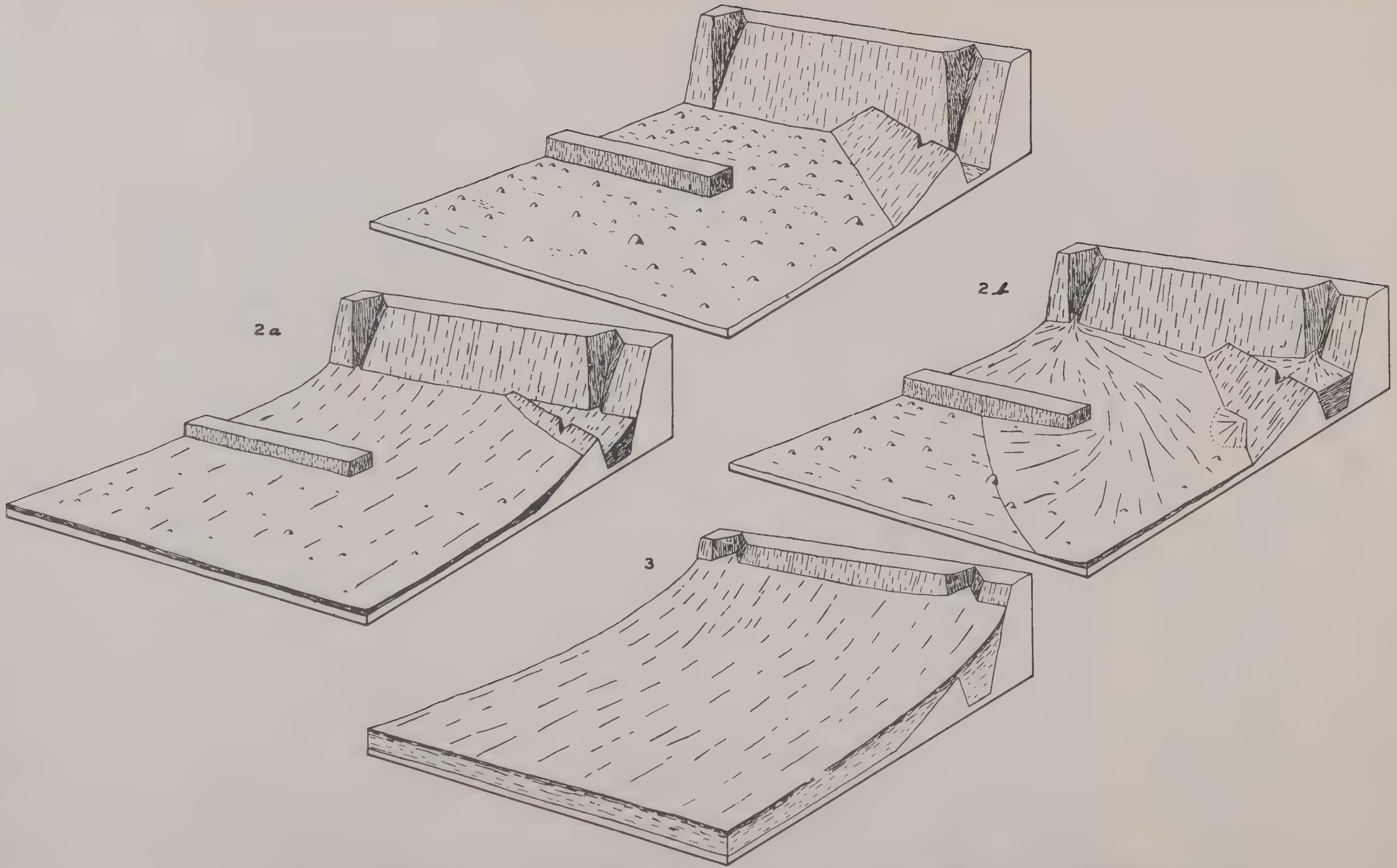
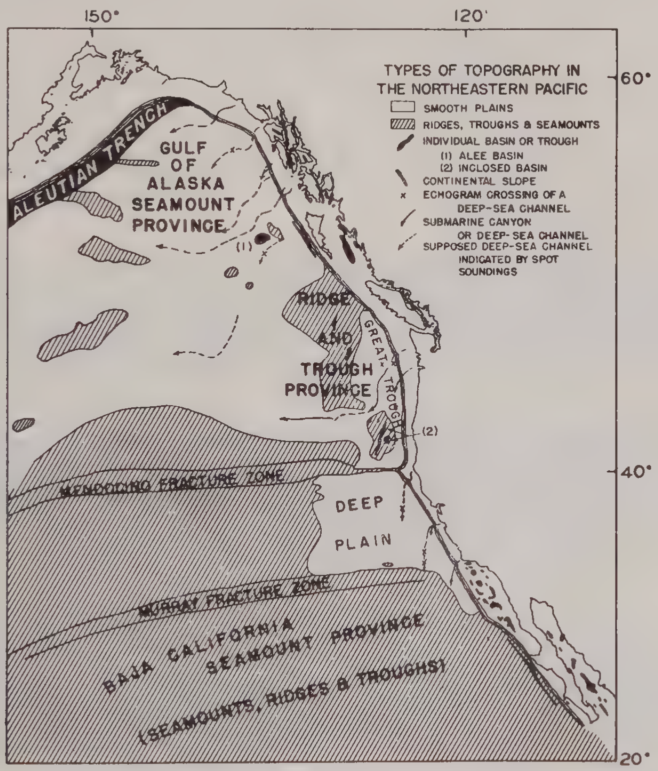


FIG. 1.—Different topography resulting from sedimentation by turbidity currents and by volume suspension in ocean. Relief about 2 miles, vertical exaggeration ×100. (1) Continental slope with submarine canyons (origin not relevant), and irregular deep-sea floor without sedimentary cover. (2a) Deposition of sedimentary blanket by volume suspension. Blanket thins from shore outward but is otherwise virtually uninfluenced by relief. (2b) Deposition of flood of sediment by turbidity currents. Submarine canyons are at apices of low flat deep-sea fans. Sediment from one canyon is ponded by tilted fault block, and comparatively thick deposit is formed. Sediment from other canyon flows around low fault block, but some alee parts

SEDIMENTARY PLAINS AND SEDIMENT TRAPS

Much of the northeastern Pacific sea floor has been divided into topographic provinces (Menard, in press) on the basis of regional depth; number of seamounts, guyots, and islands; presence of fault blocks; and the character of the micro-relief revealed by echograms, in particular whether it is irregular like a volcanic or tectonic terrane or smooth like a sedimentary plain. In relation to the present study, it is enlightening to correlate the micro-relief in various provinces with the existence of trenches and troughs and ridges at the continental margin (Fig. 2), which would act as barriers or sediment traps to turbidity currents but not to volume-suspended sediment.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TYPES OF TOPOGRAPHY IN THE NORTHEASTERN PACIFIC
SMOOTH PLAINS
RIDGES, TROUGHS & SEAMOUNTS
INDIVIDUAL BASIN OR TROUGH
(1) ALEE BASIN
(2) INCLOSED BASIN
CONTINENTAL SLOPE
× ECHOGRAM CROSSING OF A DEEP-SEA CHANNEL
SUBMARINE CANYON OR DEEP-SEA CHANNEL
SUPPOSED DEEP-SEA CHANNEL INDICATED BY SPOT SOUNDINGS
ALEUTIAN TRENCH
GULF OF ALASKA SEAMOUNT PROVINCE
(1)
RIDGE AND TROUGH PROVINCE
GREAT TROUGH
(2)
MENDOCINO FRACTURE ZONE
DEEP PLAIN
MURRAY FRACTURE ZONE
BAJA CALIFORNIA SEAMOUNT PROVINCE
(SEAMOUNTS, RIDGES & TROUGHS)

FIG. 2.—Correlation between smoothness of deep-sea floor and accessibility of area to turbidity currents. 10° Lat. equals 600 miles. Most rough areas in north half of northeast Pacific are mountainous ridges rising above vast smooth plain. Numerous deep-sea channels cross plain. Basins below general level of plain are uncommon but some lie alee of ridges and others are surrounded by ridges. In Deep Plain, sea floor is smooth near shore and deep-sea channels are numerous. Farther out, sea floor is irregular as though flood of sediment moving out from continent were not thick enough on its distal edge to cover initial relief. Baja California Seamount Province is irregular throughout. It is separated from continent by basins which act as traps for turbidity currents, and no deep-sea channels exist in province.

The extensive plains which are so typical of the Gulf of Alaska Seamount Province, the Ridge and Trough Province, and the Deep Plain of the Northeastern Pacific are very smooth (Fig. 3). The floor of the Gulf of Alaska slopes gently toward the southwest from the base of the continental slope in a smooth concave-upward curve resembling a graded profile (Menard and Dietz, 1951). Most of the continental margin grades smoothly into the deep sea and no barrier to turbidity currents exists. The only major turbidity-current trap is a long shallow trough at the base of the continental slope off the Queen Charlotte Islands, and soundings suggest that a part of the trough may have been filled and thereby bridged by turbidity currents. The trough is associated with a band of major earthquake epicenters, suggesting that it may be in process of formation. Inasmuch as every criterion shows that the other parts of the Gulf of Alaska Seamount Province and the adjacent continental slope are in an "old" stage of a geomorphological cycle (Menard and Dietz, 1951; Dietz, 1952), the trough indicates local rejuvenation. It seems not unlikely that the smooth slope of the deep-sea floor may have been building up as a sedimentary apron since long before the Quaternary period. If so, the smoothness would be unchanged even though the formation of the Queen Charlotte trough would, at least temporarily, cut off the supply of sediment.

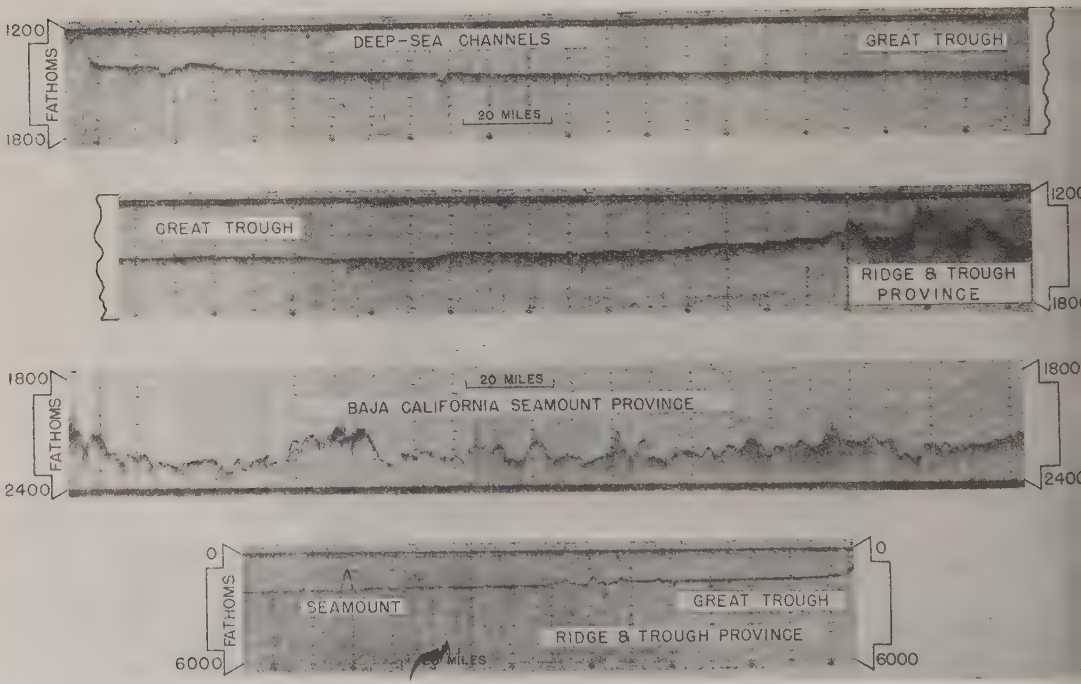


FIG. 3.—Echograms showing differences in micro-relief of smooth sedimentary plain crossed by deep-sea channels (Ridge and Trough Province) and micro-relief of rough area (Baja California Seamount Province).

Numerous ridges form dams to the movement of turbidity currents in the Ridge and Trough Province but the sea floor slopes parallel with the ridges as though sediment moved past rather than over them. The only low places in which the bottom is not smooth appear to be depressions completely surrounded by ridges so that they are inaccessible to turbidity currents.

The Deep Plain slopes smoothly out to sea from the base of the continental slope without any interruptions by troughs or trenches.

The micro-relief of the Baja California Seamount Province is rough (Fig. 3). Echograms have been obtained along approximately 15,000 miles of track in this province and no extensive smooth bottom has been found except for a very limited area at the base of the Patton escarpment. Unlike the provinces on the north, basins are very common in the deep-sea floor. Several echograms show alternating basins and ridges for almost the whole distance between Hawaii and southern California. Basins are also characteristic of the eastern or continental margin of the province which reaches from the Transverse Ranges in California to the southern end of the Gulf of California (Fig. 2). The largest basin is the Gulf of California separated by the peninsula of Baja California from the open Pacific. The gulf is about 60 miles wide and ten times as long, and the floor contains several large local depressions (Shepard, 1950). Smaller basins separate the Pacific coast of southern California and Baja California from the Baja California Seamount Province of the deep-sea floor. Most prominent of these are the basins of the Continental Borderland (Shepard and Emery, 1941) which extend off all of southern California and the northern half of Baja California; but narrow troughs lie at the base of the continental slope off the southern half of Baja California as well. The Baja California Seamount Province is separated from the continent by possible sediment traps along its whole eastern border. Smooth bottom commonly is found in the basins and the troughs; it indicates how effective these traps have been.

In summary, all of the deep-sea topographic provinces off western North America, except the Baja California Seamount Province, are characterized by vast plains of smooth bottom. None of the provinces is separated from the continent by basins or troughs except the Baja California Seamount Province. Basins and troughs are effective sediment traps for turbidity currents but not for sediment moved by volume suspension. It is apparent that the distribution of sedimentary plains in the northeastern Pacific can be explained by assuming that the dominant means of transportation and deposition is by turbidity currents.

Other explanations are possible. Major rivers debouch on the continental sides of all the provinces, except the Baja California Seamount Province (exclusive of the Colorado River which has its mouth 600 miles from the open sea); therefore, if deep-sea sediment is locally derived by volume suspension, the rough bottom of the Baja California Seamount Province may be ascribed to the absence of sources of sediment. Likewise, the distribution of sedimentary plains may be explained in terms of the "veil of leutite" hypothesis, if it is assumed that a once smooth sea floor in the Baja California Seamount Province has recently or comparatively recently been faulted, whereas the remainder of the northeastern Pacific has not been deformed. This explanation dismisses any correlation between sediment traps and deep-sea plains as a coincidence.

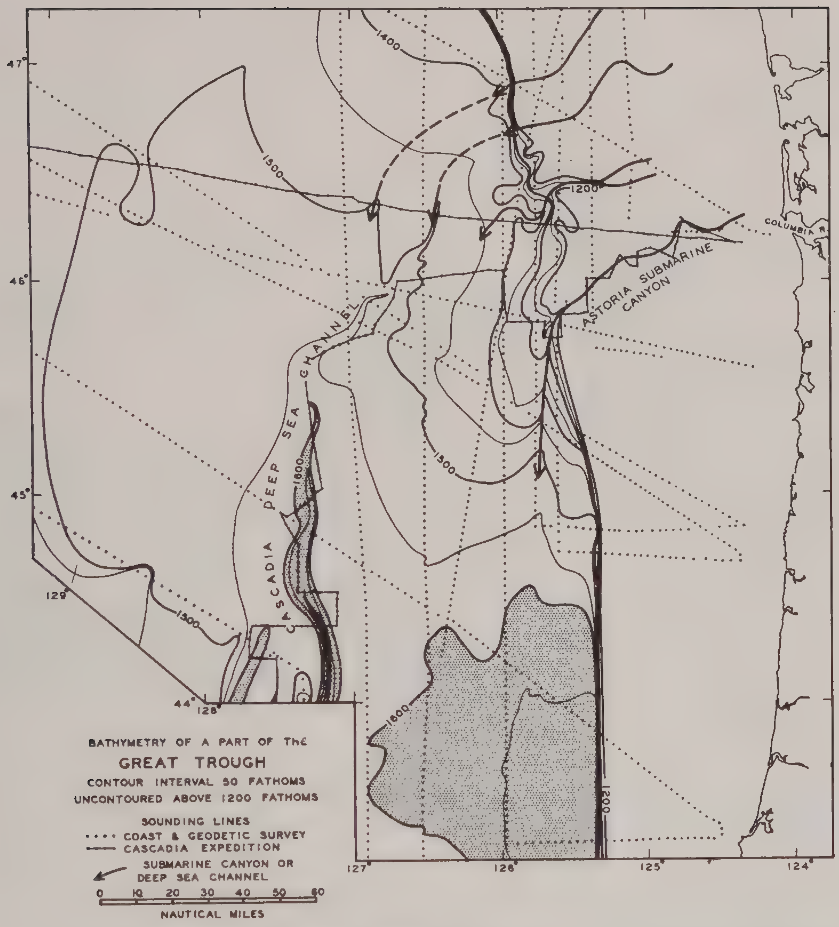
RIDGES, DAMS, AND SLOPE DIRECTIONS

A ridge has no appreciable effect on the direction of slope of a sedimentary plain on the deep-sea floor if the sedimentation is dominantly from volume suspension. The effect may be very marked if sedimentation is dominantly from turbidity currents because a ridge may be a dam athwart the flow, and the turbidity current may be deflected or ponded. The Ridge and Trough Province provides two examples of the influence of ridges on the slope of adjacent sedimentary plains. Other examples could be cited, but it is believed that these suffice to show a definite relationship.

The sea floor of the Great Trough at the foot of the continental slope off Oregon and Washington is extremely smooth, except where it is crossed by deep-sea channels (Figs. 3, 4). The floor has a consistent slope direction but it is parallel with the continental margin rather than perpendicular to it in the normal manner. This peculiar relationship can not be explained by the deposition of a continental apron from volume suspension unless the improbable assumption is made that an initial topography had the same slope as the present sea floor. It remains to be seen if the slope direction can be explained by turbidity-current deposition.

A band of submarine mountains rises above the western edge of the trough plain. The mountains include many volcanoes but long narrow ridges are more typical. The band intersects the continental slope just south of the Queen Charlotte Islands, is about 150 miles west of the continental slope at Latitude 45° N., and approaches the slope again off northern California. Except on the south, the mountains appear to form a continuous dam to the movement of turbidity currents but the area is not so well sounded as to exclude the possibility of low passes in some other places.

Consider turbidity currents flowing out from the many submarine canyons on the continental slope off Oregon and Washington into an initially rough-bottomed deep-sea basin. Individual deep-sea fans would form at the mouths of submarine canyons, and these fans would gradually coalesce to form an alluvial apron sloping toward the west (or southwest because of the tendency for turbidity currents to hook toward the left). The apron would be extended west until it became ponded against the mountains dam. The sedimentary plain would gradually be aggraded until in some place the surface rose level with a low pass in the mountains. Turbidity currents reaching this pass would flow out so that in the vicinity of the pass the plain would no longer be aggraded. The whole surface of the plain would then be slowly graded so that turbidity currents flowing onto the plain at any point would flow toward the low pass. This appears to be the present condition in the Great Trough off Oregon and Washington. Toward the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COLUMBIA R.
ASTORIA SUBMARINE CANYON
CASCADIA DEEP SEA CHANNEL
BATHYMETRY OF A PART OF THE
GREAT TROUGH
CONTOUR INTERVAL 50 FATHOMS
UNCONTOURED ABOVE 1200 FATHOMS
SOUNDING LINES
COAST & GEODETIC SURVEY
CASCADIA EXPEDITION
SUBMARINE CANYON OR DEEP SEA CHANNEL
0 10 20 30 40 50 60
NAUTICAL MILES

FIG. 4.—Bathymetric chart of part of sea floor off northwestern United States. Submarine canyons and the deep-sea channels hook toward left. Cascadia Deep-Sea Channel has been deflected west by deep-sea fan at mouth of Astoria Submarine Canyon.

west the basin is almost flat, but it has a gentle slope toward the south where a pass exists through the mountains.

A similar sequence of events suffices to explain the slope of a less extensive sedimentary plain in the southeastern part of the Great Trough at the base of the continental slope off northern California. Several large submarine canyons lead down to a smooth plain about 270 miles long and 20–60 miles wide. The plain is separated from the principal plain of the Great Trough only by the deep-sea fan at the mouth of the Astoria Submarine Canyon. Cascadia Deep-Sea Channel which is now displaced to the west by the fan (Fig. 4) may once have flowed across both plains. The plain is essentially flat toward the west, and slopes gently toward the south—parallel with the trend of the continental margin. On its western side the plain is bounded by a ridge in the Ridge and Trough Province. Toward the south the plain appears to slope into a narrow channel which leads through a mountainous pass to the deeper sea floor on the west.

INCLOSED AND ALEE BASINS

Local basins are rare in smooth-bottomed areas of the deep-sea floor: not one is known to exist on the whole continental apron on the Atlantic side of North America; on the Pacific side, no basins have been found on the continental apron of the Deep Plain, and only two are known on the continental apron of the Gulf of Alaska Seamount Province; however, scores are known in the Ridge and Trough Province. The formation of these basins clearly is a function of the rate and type of sedimentation and is of interest here.

Only one ridge rises above the continental aprons of the three smooth-bottomed areas—the Atlantic side of North America, the Deep Plain, and the Gulf of Alaska Seamount Province; one of the two basins in these areas lies on the downslope side of the ridge (Fig. 5). The formation of the basin can be explained in terms of deposition of the apron by turbidity currents but not by deposition by volume-suspension. Consider deposition of a sedimentary apron on a flat sea floor from which rises one ridge transverse to the direction of sediment movement. Volume-suspended sediment would settle on all sides of the ridge and the smooth aggrading surface of the apron would not be interrupted by a basin. Turbidity currents, however, would be deflected around the ridge and a basin would be formed on the lee side of the ridge as the turbidity currents aggraded their channels. Basins with this origin may be called "alee basins." The existence of an alee basin will depend on the length of the ridge and its orientation relative to the direction of flow of turbidity currents. No basin will be formed if currents are able to bend around the lee side of the ridge, but such bending may be inhibited by the presence of natural levees which confine the flow.

Two prominent basins in the Ridge and Trough Province off northern California and Oregon appear to be not only on the lee side of a ridge but to be completely inclosed by ridges. One is roughly circular, has an area of about 200 square miles and is about 1,300 feet deeper than the smooth sedimentary plain at the north, east, and south outside the encircling ridges. The other is a narrow trough about 120 miles long, 5 miles wide, and 1,800 feet deeper than the sedimentary plain outside the sub-parallel ridges which inclose it. The sedimentary plains are very smooth, have gentle slopes, and are traversed by deep-sea channels, some of which are known to lead out from submarine canyons. They show every indication of being the products of aggrading turbidity currents. The basins, on the other hand, have very irregular floors, indicating deposition has been very thin although cores in both basins show that some deposition has occurred. The existence of these and other inclosed basins can be explained if the dominant

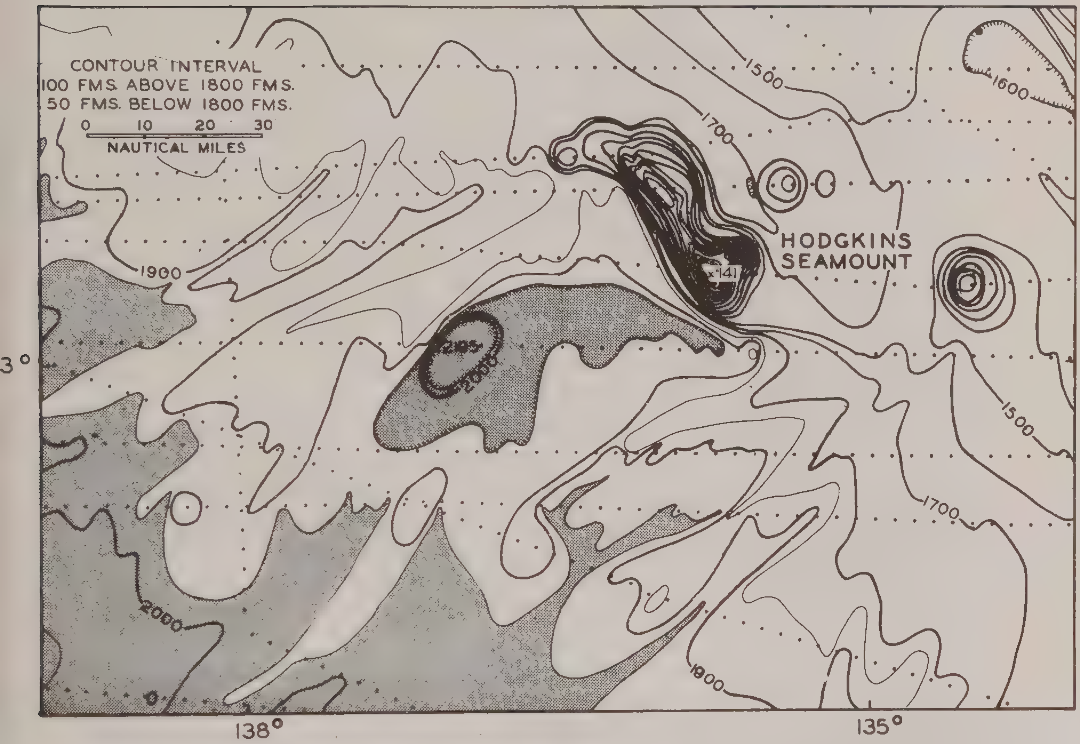

FIG. 5.—Bathymetric chart of part of sea floor in Gulf of Alaska. Deep basin is on down slope or lee side of high ridge

means of sedimentation is by turbidity currents and the currents are barred from entering by the ridges. It can not be explained by sedimentation from volume suspension unless the basins are structural lows and have been formed too recently to be filled.

One other basin of interest lies at the base of the continental slope off the Queen Charlotte Islands. This long thin basin appears to be a fault trough, and the correlation between its trend and position and the trend and position of a band of earthquakes suggests that it may still be sinking and at a rate too fast for sediment to fill it. The long thin basin in the Ridge and Trough Province appears to be a fault trough, and the other basin in this province and the basin alee of Hodgkins Seamount lie in or near areas which are seismically active. It is possible, therefore, that all of these basins sank very recently, or are sinking. If so, they might not have been filled, regardless of the dominant type of sedimentation. If basins were common in the smooth sedimentary plains this explanation would appear adequate. Inasmuch as most basins are ringed by ridges or are alee of ridges, it appears more plausible that sedimentation has filled all but the deepest or most active exposed basins and left the protected basins unfilled.

DEEP-SEA CHANNELS AND DEEP-SEA FANS

DIRECTION OF FLOW OF TURBIDITY CURRENTS

Regardless of the method of flow, it may be expected that a turbidity current debouching from a submarine canyon onto the relatively flat sea floor will be checked in velocity and will deposit some of its sediment in a deep-sea fan.[3] The available evidence for the existence of such deep-sea fans is fragmentary, but the best surveyed areas give the strongest support. "Deltas" or "delta-like fans" have been found associated with submarine canyons, notably the Hudson (Ericson, Ewing, and Heezen, 1951), La Jolla (Menard and Ludwick, 1951), and Monterey (Dill, Dietz, and Stewart, 1954) canyons. Similar fans appear to be associated with the Astoria Canyon and the Cascadia Deep-Sea Channel (Fig. 4), and the Arguello and Delgado canyons (Fig. 6), as well as many of the other canyons shown by Shepard and Emery (1941).

Deep-sea channels extend across the fans at the mouths of submarine canyons. The presence of these channels proves that part of the turbidity-current flow on the sea floor is channelized (Menard and Ludwick, 1951); therefore, it is unlike the flow observed in laboratory experiments, or the flow deduced from the shape of sedimentary beds supposedly deposited by turbidity currents (Kuenen and Migliorini, 1950), or the flow deduced from the time and position of cable-breaks (Kuenen, 1952). This inconsistency might not be significant if deep-sea channels were few, but recent exploration with echo-sounders capable of showing such relatively small features suggests that they are very common.

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[3] The nomenclature for constructural landforms on the deep-sea floor is confused, as might be expected in a new field in which the evidence is fragmentary. Two of these landforms of particular interest are the "fans" or "deltas" shaped like gently sloping cones and found at the mouths of many submarine canyons, and the "channels" or "valleys" which lead across the "fans" from the mouths of the submarine canyons toward the deep sea. The earliest description of channels on the deep-sea floor known to the writer is in Shepard and Emery (1941) where they are called "valleys," "troughs," and "channels" because the soundings then available were not adequate to show that all the channels were the same landform. Subsequently, channels on the deep-sea floor have been called "canyons" or "mid-ocean canyons" (Ericson, Ewing, and Heezen, 1951, 1952; Ewing *et al.*, 1953); "channels" or "deep-sea channels" (Menard and Ludwick, 1951; Dietz, 1952; Dill, Dietz, and Stewart, 1954); and "valleys" or "outer valleys" (Shepard, 1951, 1952; Tolstoy, 1951). It is the writer's opinion that the term "canyon," with its connotation of high steep sides, should not be applied to landforms which typically are a few miles wide and only a few hundred feet deep; moreover, it would be unfortunate to link the genetically controversial term "submarine canyon" to these deep-sea channels for which few geologists would advocate a subaerial origin. The choice between "valley" and "channel" is more difficult, but "valley" has a connotation of erosion which may not be justified. The writer prefers the term "deep-sea channel."

The gently sloping cones at the mouths of submarine canyons were recognized by Shepard and Emery (1941) and called "deltas." This term has continued in use (Ericson, Ewing, and Heezen, 1951, 1952; Menard and Ludwick, 1951; Dill, Dietz, and Stewart, 1954) but as Kuenen (1952, p. 472) has observed, "so-called deltas are more like fans," and such terms as "delta-like fan" (Menard and Ludwick, 1951), "depositional fan" (Shepard, 1952), "delta-fan" and "delta-like apron" (Dill, Dietz, and Stewart, 1954), "coalescing alluvial plains" (Ericson, Ewing, and Heezen, 1951), and "apron" (Dietz, 1952) have also been used. Of the more conventional terms, the choice appears to be between "delta" and "fan" and depends on the assumed former position of sea-level. A delta is a deposit of sediment formed where a river enters a lake or the ocean, that is, in the vicinity of a shoreline. A fan is a deposit of sediment formed where the bed slope of a river markedly flattens. If, as Shepard (1952) argues, the shoreline was near the level of the mouths of submarine canyons when the sediment was deposited, the deposit should be called a delta. If, on the other hand, the sediment was deposited by turbidity currents because of a decrease in bed slope, the deposit should be called a fan. In the absence of any recognized term without genetic connotations, "deep-sea fan" is used in the present paper.

Only the Cascadia, Monterey, and La Jolla deep-sea channels have been surveyed for any significant distance in the northeastern Pacific, but ten other channels in the area have been crossed in several places at random and are shown on at least one echogram. Approximately ten more doubtful channels can also be seen on echograms. Detailed contouring of the unpublished soundings of the Coast and Geodetic Survey indicates the presence of many other channels. The Cascadia and Dickens deep-sea channels appear to be at least 500 miles long, although the continuity of the channels is by no means proved. The slopes of the supposed channels are constant at about 0.001 except near the continental apron (Fig. 7). These slopes closely approximate the slope of the surveyed part of Cascadia Deep-Sea Channel; hence, they tend to confirm the reality of the outer part of the channels. The Cascadia Deep-Sea Channel reaches a very smooth, sloping plain which continues far toward the west. The channel itself can not be traced, but the slope of the plain is also about 0.001, so the gradient on which any turbidity currents would flow is relatively constant for more than 1,000 miles. The actual bed slope of a channel in this area would probably be somewhat less because of meander-like bends which would lengthen the distance of travel; it might approach the slope of 0.00045 of the Northwest Atlantic "Mid-Ocean Canyon" (Ewing *et al.*, 1953).

The large number and great length of deep-sea channels show that a significant proportion of turbidity-current flow in the oceans is not in the form of sheet flow. The question may be raised whether any of it is sheet flow and whether the mode of deposition deduced from the sheet-like form of supposed turbidity-current deposits is correct. Some answers to these questions and others concerning the distribution of grain sizes in turbidity-current deposition are given by considering the direction of flow of turbidity currents as indicated by deep-sea channels.

Deep-sea channels on deep-sea fans appear to have one outstanding characteristic: most, and possibly all that are not in structural troughs, hook toward the left. Inasmuch as important conclusions follow if this appearance is real, rather lengthy documentation is attempted.[4] Four deep-sea channels on deep-sea fans have been surveyed along the west coast of North America; without exception all hook toward the left compared with the trend of the connecting submarine canyon. ("Left" is also "south" and it is not clear which term is significant.) The Hudson Deep-Sea Channel is the only other one which has been surveyed where it crosses a fan. It appears that the channel is confined in a general way to a structural trough formed by a curve in the continental terrace; there-

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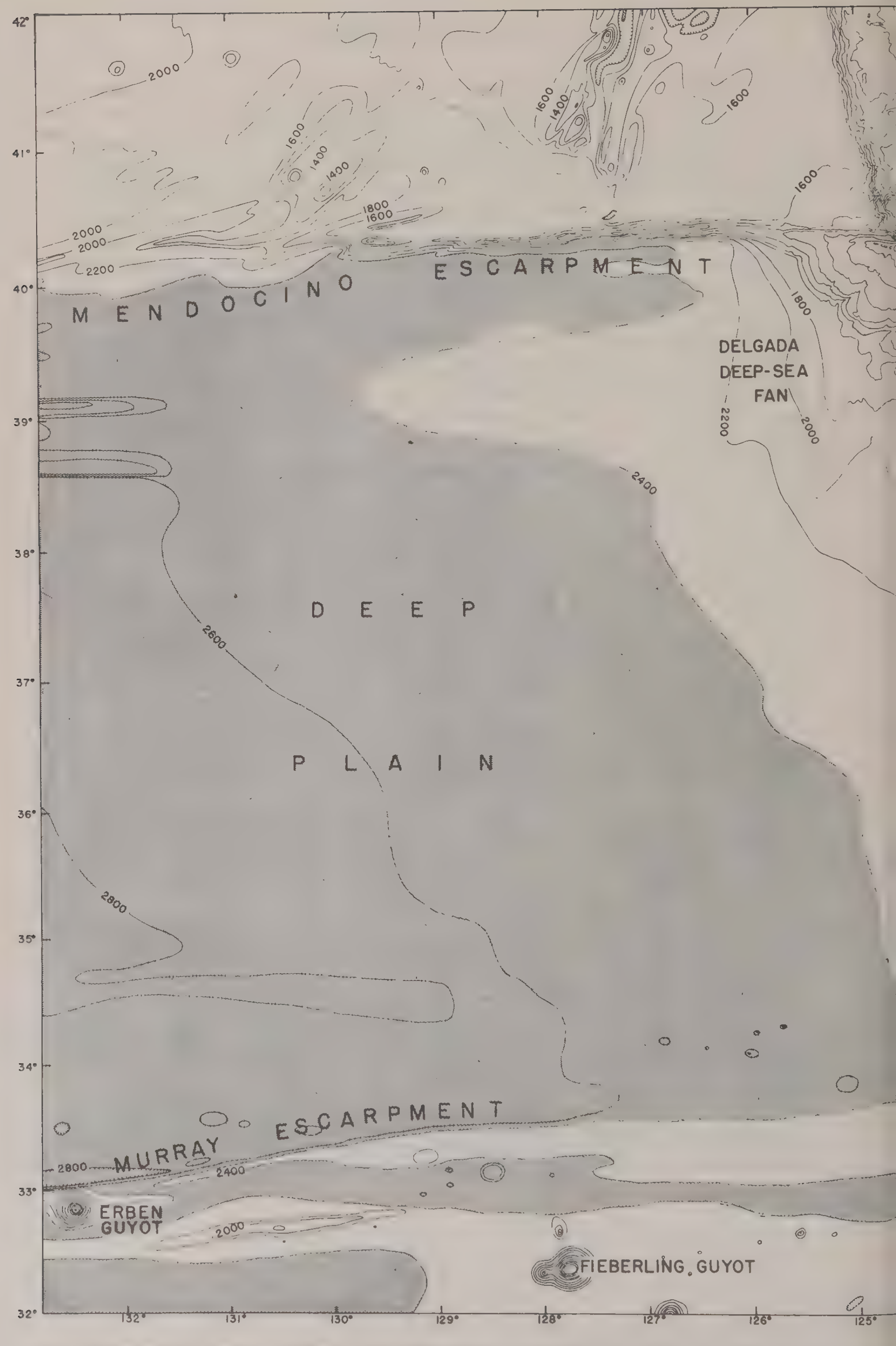
[4] The general fact that deep-sea channels are located along the sides of fans was first noted by Shepard and Emery (1941, p. 84). "In all these cases these channels follow the side of the 'delta' rather than cutting the central portion. All the channels diverge from the general trend of the submarine canyons inside."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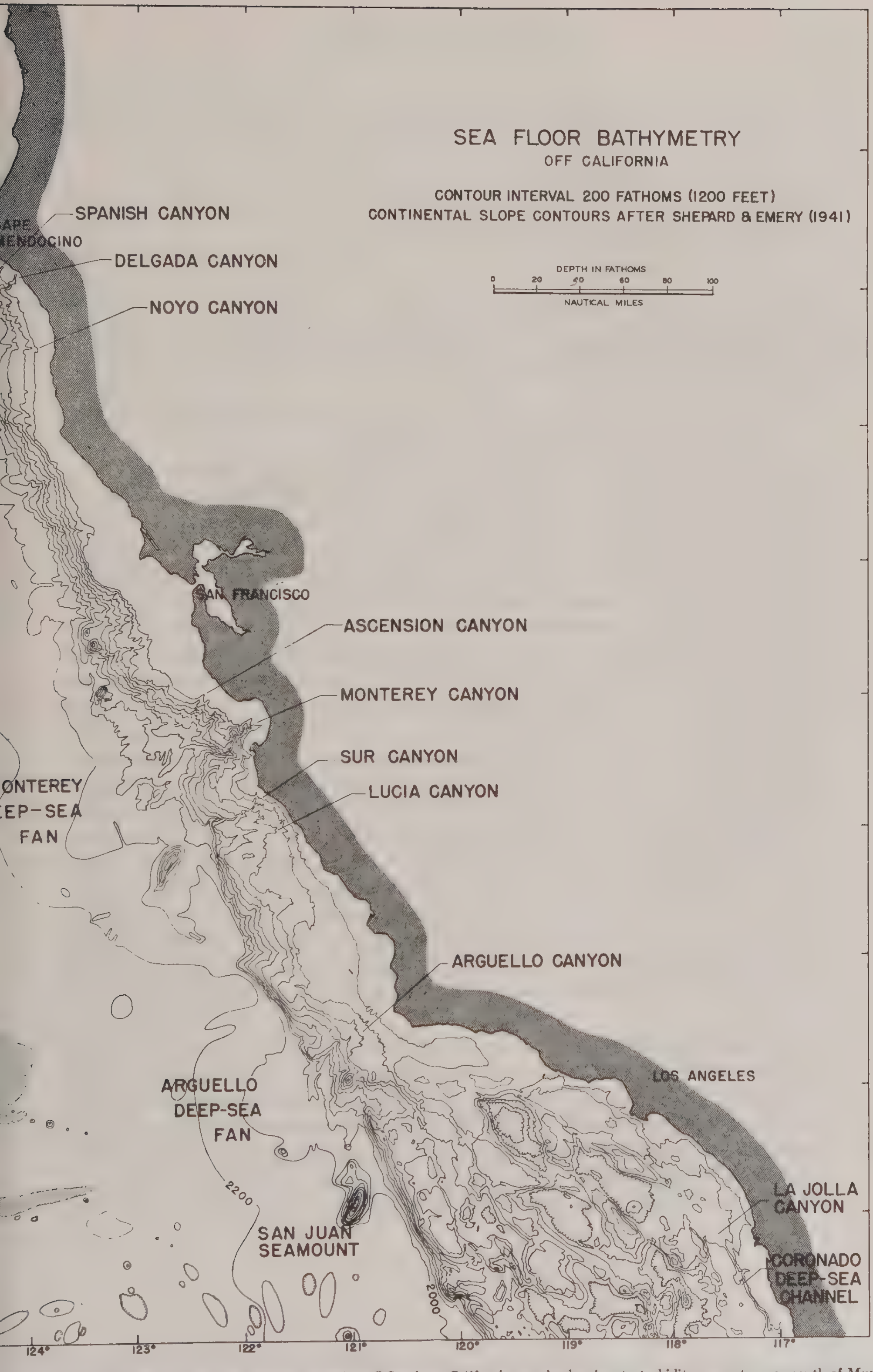
126°
125°
2000
1600
1400
1800
2200
2400
2600
2800
MENDOCINO ESCARPMENT
DELGADA DEEP-SEA FAN
DEEP PLAIN
MURRAY ESCARPMENT
ERBEN GUYOT
FIEBERLING GUYOT

FIG. 6.—Bathymetric chart of sea floor off California. From shoreline to base of continental slope; chart is taken from Shepard and Emery (1941) Three great deep-sea fans lie at mouths of Delgada, Monterey, and Arguello canyons, and continental slope is notably more dissected around thes three (and associated canyons or tributaries) than elsewhere. Deep-sea channels hook left from mouths of canyons. As ridge above Mendocino E carpment acts as dam to turbidity currents, deep area on south can not be filled from north. Instead, both areas have smooth sea floor sloping wes


SEA FLOOR BATHYMETRY
OFF CALIFORNIA
CONTOUR INTERVAL 200 FATHOMS (1200 FEET)
CONTINENTAL SLOPE CONTOURS AFTER SHEPARD & EMERY (1941)
DEPTH IN FATHOMS
0
20
40
60
80
100
NAUTICAL MILES
SPANISH CANYON
APE
MENDOCINO
DELGADA CANYON
NOYO CANYON
SAN FRANCISCO
ASCENSION CANYON
MONTEREY CANYON
SUR CANYON
LUCIA CANYON
ONTEREY
EP-SEA
FAN
ARGUELLO CANYON
LOS ANGELES
ARGUELLO
DEEP-SEA
FAN
2200
SAN JUAN
SEAMOUNT
2000
LA JOLLA
CANYON
CORONADO
DEEP-SEA
CHANNEL
124°
123°
122°
121°
120°
119°
118°
117°

e above Murray Escarpment also acts as dam. As basins off Southern California are also barriers to turbidity currents, area south of Murray rpment (Baja California Seamount Province) is generally inaccessible to turbidity currents and is rough. Fan of Arguello Canyon seems to have ounted easternmost part of Murray Escarpment, and small flood of sediment has covered irregular topography in this one small area of whole California Seamount Province.

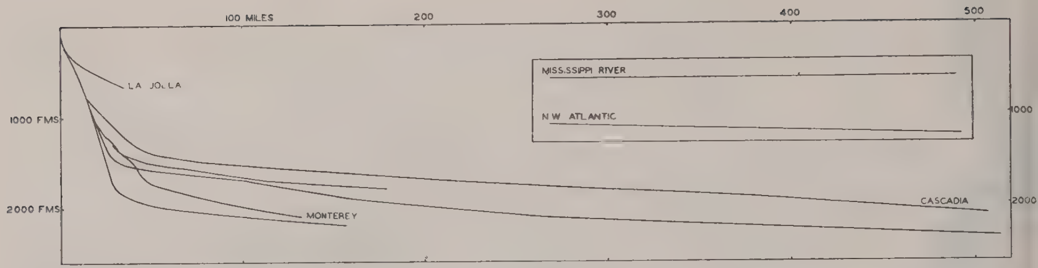


FIG. 7.—Longitudinal profiles of submarine canyons and associated deep-sea channels in northeastern Pacific Ocean, showing general similarities and compared with Mississippi River and Deep-Sea Channel of Northwest Atlantic which has not been traced to a submarine canyon.

fore, no prominent hook in the channel would be possible unless the turbidity currents could form a channel while flowing uphill.

Soundings are adequate in some places to permit tracing the course of deep-sea channels with reasonable assurance even though special surveys have not been made. Charts of the California coast (Shepard and Emery, 1941) show seven submarine canyons connected with what the writer would call deep-sea channels. One of these is the Monterey Deep-Sea Channel which unquestionably hooks toward the left (and south), but has already been counted as a specially surveyed channel. Of the remaining six, the Arguello, Noyo, and Delgada deep-sea channels hook toward the left; Lucia probably hooks toward the left but can not be traced with assurance; and the Pioneer and Sur deep-sea channels hook left for only a few miles and then bend right to the edge of the charts. The right bend in the Pioneer Channel occurs where it approaches the Guide Seamount from the north, and the bend in the Sur Channel is at the northern edge of the fan of the Lucia Deep-Sea Channel and of the Davidson Seamount. The right bends, therefore, may show merely that the tendency of turbidity currents to hook left is not so strong that they run uphill.

The unpublished soundings of the Coast and Geodetic Survey show several deep-sea channels off Oregon and in the Gulf of Alaska. Of these, the Cascadia Deep-Sea Channel has been surveyed and found to hook left. Three other nearby channels appear to hook left, and of them, the Astoria Deep-Sea Channel almost certainly does so. In the Gulf of Alaska the two most prominent channels hook left on their fans but the soundings are not adequate to show whether all others do so.

In summary, of the fifteen deep-sea channels which are surveyed or well sounded in the vicinity of their alluvial fans, twelve hook left, one probably hooks left, and two hook left for short distances but bend right where such a bend is required for the channel to slope downhill. This type of evidence for a left hook in the course of deep-sea channels may be convincing by itself, but other evidence may be adduced.

Many crossings along courses perpendicular to the continental apron of western North America show one to three deep-sea channels near the top of the apron. Crossings parallel with the general contours of the apron are relatively free of such channels. This relationship was particularly noteworthy when a line approximately along the 2,200-fathom contour was sounded for the whole length of central California. In this area, numerous well known submarine canyons dissect the continental slope and lead into deep-sea channels, and the continental apron grades smoothly out to sea into a sedimentary plain which extends at least to a depth of 2,600 fathoms. The topography shows clearly that sediment has been deposited from the continent outward across the area of the profile but only one channel was recognizable. It appears that the channels at the top of the apron must bend or hook rather than trend down the regional slope of the apron. The slope in this area, therefore, is not produced by turbidity currents flowing in channels.

ORIGIN OF THE LEFT HOOK

Twelve deep-sea channels off western North America certainly hook left (which is also south); none is known to hook right or trend straight out from the continental slope. The number of observations is not large, but it is enough to show that a real phenomenon is being observed. It is a reasonable approximation to consider that the channels are all in the most sinistral third of the available half-circle of arc of directions in which they might trend from the mouth of a submarine canyon at the base of the continental slope. Consequently, the odds are only about 3^{-12} that the twelve channels which hook left represent merely a chance sample from a group of channels which trend in all directions.

Only three plausible hypotheses of the origin of left (or south) hooks have been conceived.

1. Ocean currents exert a southward component and cause the turbidity currents to hook where they are slowed at the base of the continental slope.

2. The abyssal sea floor off western North America has been uniformly fractured by a series of step faults down on the south side. The hooks in the channels merely reflect adjustment to the slope of initial topography.

3. Some characteristics of the flow itself cause it to turn toward the left (south).

Quantitatively the first hypothesis appears improbable because it requires ocean currents with a significant southerly velocity at a depth of at least 3,000 meters and the California Current is negligible at a depth of only 500 meters (Sverdrup, Johnson, and Fleming, 1942).

The second hypothesis—control of slope by initial topography—might appear to apply to the basins of the Ridge and Trough Province and of the California Borderland, but the Deep Plain slopes about west-southwest and the deep-sea channels on the eastern margin of the plain trend slightly east of south. In other words, they do not trend down the regional slope; therefore, even if the slope were produced by block faulting, the faulting would not explain the channel trend.

The third hypothesis remains. Coriolis force—the tendency for any moving object to deviate from a straight path because of the deflecting force of the earth's rotation—acts on all currents in the ocean and must be considered as a possible cause of the left hook of turbidity-current channels. Unfortunately for simplicity of discussion, Coriolis force causes a deviation to the *right* in the northern hemisphere. Bates (1953) has considered the effect of Coriolis force on various types of flow of interest in the formation of deltas. He mentions that turbidity flows could turn to the right through an entire inertial circle because of Coriolis force; but, inasmuch as the evidence available to him indicated no such complete turn, he proposed that a tilting of the surface of the flow—so that it would be higher on the right than on the left—would be induced according to principles well known in oceanography. The tilting could cause the flow to trend toward the right parallel with depth contours instead of down the bed slope. It would further produce higher natural levees on the right side of the flow than on the left. The prediction regarding the height of natural levees is confirmed by surveys of the sea floor of western North America, and Bates' explanation appears satisfactory on this point. However, turbidity-current channels hook left and no direct reaction of the flow to Coriolis force is capable of causing it to bend toward the left in the northern hemisphere.

Coriolis force might produce a left hook of turbidity currents, however, according to the following reasoning—the wording of which applies only to the northern hemisphere.

1. A turbidity current flowing down a submarine canyon is confined so that it can not curve toward the right, despite Coriolis force. However, the top surface of the turbidity current is affected so that in transverse profile it tilts from right to left.

2. When the turbidity current debouches from the mouth of a submarine canyon onto the deep-sea floor, it forms natural levees along the sides of its channel, and the right-hand levee is higher because of the tilting of the turbidity-current surface.

3. The position of a subaerial stream channel on an alluvial fan at any given time is random, and a symmetrical deposit is formed. When one sector of the fan becomes higher than the others, some chance occurrence causes the channel to shift from its bed and it remains in a lower sector either at the right or at the left of its earlier channel.

4. The initial position of a turbidity-current channel on a deep-sea fan might also be random although the action of Coriolis force would tend to confine it to the right-hand quadrant.

5. As sedimentation continued, however, the asymmetry in the cross section of the channel would introduce a bias into the direction of migration of the channel. Unlike a subaerial stream channel, a turbidity current breaking out of an aggraded channel and migrating to some less elevated sector would always tend to move toward the left because the natural levee on that side is lower

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than the one on the right. Regardless of the initial position of the turbidity-current channel, therefore, a series of migrations from elevated sectors would eventually bring it into a sector far on the left. In fact, the channels seem to have migrated as far toward the left as they can go without flowing uphill on the continental apron.

A general rule for the orientation of leveed turbidity-current channels may be proposed. "A turbidity current channel flanked by levees has a tendency to deviate from a straight line which varies directly with the amount of the deflecting force of the earth's rotation but is in the opposite direction." As the intensity of the deflecting force of the earth's rotation is directly proportional to the sine of the latitude, the tendency to hook will be correspondingly small in the equatorial regions. The deflecting force of the earth's rotation is toward the right in the northern hemisphere and toward the left in the southern hemisphere; the tendency to turn has the opposite sense.

MODE OF FLOW AND ORIGIN OF FANS

If a turbidity current debouching from a submarine canyon promptly hooks left, what forms the deep-sea fan which occupies roughly a semi-circle? Subaerial alluvial fans have a regular form like a half of a cone which is produced by the meandering of a stream across the area. Deposition occurs along a course until the sector becomes higher than others, and some chance occurrence shifts the course to a lower sector. This process of meandering can not produce the submarine alluvial fans, because the channels remain in the same sector. Some other process is required, a process that spreads sediment in a semi-circle around the mouth of a submarine canyon.

A suitable process would be the very sheet-flow of turbidity currents which the existence of turbidity current channels seemed to question. It is entirely possible that at times comparatively small turbidity currents flow down submarine canyons and follow the bends in deep-sea channels, and at other times large turbidity currents flow over the deep-sea channel and spread out in a semi-circle as a kind of vast sheet flow. However, the two types of flow need not be separate. A very pronounced vertical concentration gradient may be expected in turbidity currents, especially if coarse sand and gravel are carried in suspension (Menard and Ludwick, 1951). A large turbidity current with a vertical concentration gradient might split at the mouth of a submarine canyon. The dense bottom layer of coarse sediment would follow the channel but the more tenuous top layer might be higher than the channel levees and thus would flow in a random direction or toward the right instead of hooking left along the channel. The top layer would slowly spread radially because it would be denser than the surrounding water.

GEOLOGICAL IMPLICATIONS AND CONCLUSIONS

Turbidity currents are important agents, transporting and depositing sedi-

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ment in the near-shore part of the abyssal northeastern Pacific. Witness the following facts.

1. Deep-sea channels ascribed to turbidity currents are widespread on the sea floor.

2. Areas which turbidity currents can reach, in general, are smooth plains. Areas which turbidity currents can not reach because basins form sediment traps between the deep-sea floor and the continents, in general, are areas with rough micro-relief.

3. The smooth sedimentary plains do not necessarily slope away from the continents. Some slope southward parallel with the continental margin in places where the westward flow of turbidity currents is obstructed by mountains which act as dams.

4. Deep basins with irregular bottom are common in places which are shielded from turbidity currents by ridges or troughs. Similar basins have not been found in places which are not so shielded except for one which is in a seismically active area.

The geological history of a submarine region apparently can be as complicated as that of a subaerial region. Consider the sediment deposited in the Ridge and Trough Province. One basin will be filled very rapidly because it lies on the course of a turbidity-current channel while another basin only a few miles away collects only pelagic organic remains and a thin layer of sediment moved by volume suspension. Later, after the turbidity current aggrades its channel, the ridge protecting the unfilled basin will be surmounted and sediment will pour into the basin. If the original channel is graded to some outlet by that time, the surface of the surrounding plain will become a disconformity, and little deposition will occur. The rate of deposition in the two areas will be reversed.

Deep-sea channels seem to show that turbidity currents flow at an angle to the slope instead of directly down slope. Most surveyed channels in the northeastern Pacific hook sharply toward the left across the alluvial fans at the mouths of submarine canyons. Because of the trend of the coastline, a hook toward the left is also a hook toward the south. It is not evident whether "left" or "south" is the direction related to the origin of the bend, but only a bend toward the left has been explained. For the present the most promising working hypothesis is that: (1) the surface of the flow becomes tilted in response to Coriolis force; (2) consequently, natural levees are higher on the right than on the left; and (3) the height difference biases "random" changes in the position of the channel so that all changes are toward the left.

Regardless of origin, some conclusions warrant discussion. Some turbidity currents hook upon emerging from the mouth of a submarine canyon (perhaps without exception if initial relief does not interfere). From the evidence now available it appears that sand bodies deposited on the deep-sea floor by turbidity currents should be confined to a narrow sector (left or south side) of the alluvial fan. The implications for paleogeography are apparent. Significant deductions may be drawn regarding the direction of ancient shorelines, and location of the mouths of ancient submarine canyons. With the knowledge that both channelled and sheet-flow modes of turbidity flow probably exist, some additional progress may also be made in attempting to explain the origin of minor sedimentary structures associated with graded bedding.

Inasmuch as turbidity currents are such controversial subjects, it may be discrete to close with a negative conclusion. Sea-floor topography, as shown by the echograms available to the writer, gives no proof that turbidity currents are able to erode the deep-sea floor. Deep-sea channels, for example, may be produced by non-deposition. On the other hand, many obviously erosional submarine canyons on both the east and west coasts of North America exhibit a peculiar curvature toward the left across the contours of the continental slope. If it develops that such curvature or hooking is a characteristic only of turbidity-current flow, sea-floor topography may give convincing evidence for submarine erosion.

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OCEAN-BOTTOM ARTIFACTS*

By CARR TUTHILL and A. A. ALLANSON

THE coast of southern California, which various Chambers of Commerce have long assured us is fabulous, has made a new and somewhat unusual contribution to American science—underwater archeology! As a result of this contribution, a person who is adept at skin-diving can now gather archeological specimens and the ingredients of a seafood dinner at the same time.

At least six locations or sites in San Diego County are now known which have produced Indian artifacts in water up to 100 feet deep and as much as 2000 feet from the present shoreline (fig. 1). There undoubtedly are other sites in this area that are not yet known, as well as other sites along the coast north of San Diego County, and presumably in Baja California.

Underwater archeology *per se* is nothing new, but it is quite possible that these finds will shed some additional light on prehistoric man here, and certainly will point up the fact that many of his early littoral sites have long since disappeared under the waves.

Early man must have used the seashore as a rich source of food and must have camped near the shore to eat his meals, manufacture his crude tools, etc. Our coastline is continuously eroding into the ocean, and our present shoreline may be a spot that was well inland only a few hundreds or thousands of years ago. The corollary here is that the campsites of early man that are found along the existing coast were not shoreline sites when they were made.

In September, 1951, two boys who were diving just outside the surf-line near the La Jolla Beach and Tennis Club found a peculiar stone which they brought ashore with them, and took to the junior author for identification. He recognized it as a fragment of a small mortar, noted the locality from which it had come, and did some investigating of his own. He found a large area extending some 800 feet out from shore in which, at last count, some three hundred of the mortars have been found. He was aided in this work by Conrad Limbaugh and Andreas B. Rechnitzer of the Scripps Institution of Oceanography, and John Fleet of La Jolla. Most of the diving to recover the mortars was done in water up to 20 feet deep without the use of any kind of diving gear, although

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Contributions from the Scripps Institution of Oceanography, New Series, no. 751.

Reproduced from The Masterkey, vol.28, no.6, 1955, by permission of the Southwest Museum, Los Angeles.

intended as a light repast for the basket-weaver, as most American Indians enjoyed eating these.

The age of the cache can only be guessed at, but there is no doubt that it dates from the contact period, for in addition to the box itself it includes a number of items of Caucasian manufacture. This would place it in the post-1850's, probably somewhere just before the turn of the century. The square nails holding the box together are a type which have not been made during the last fifty years; the woman's blouse is of a style popular at least five decades ago. Also the simple ornamentation on the basketry bowl indicates that it is a fairly old example of the weaver's art. All of the evidence seems to point to an antiquity of at least fifty years for the box and its contents. Whatever its exact age, it was hidden away by a woman who obviously intended to return and use the prepared materials. For some reason she never did.

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VISITORS

AMONG recent out-of-town visitors to the Museum were the following, whom members of the staff were happy to welcome:

Mr. Hans E. Suess, United States Geological Survey, Washington.

Dr. Manuel Maldonado-Koerdell, Department of Prehistory, National Museum of Archeology, City of Mexico, who presented several of his scientific papers to the Museum library.

Mr. Carl I. Wheat, of Menlo Park, California, who did not forget to leave a copy of his latest scholarly cartographic publication, "Mapping the American West, 1540-1857," published by the American Antiquarian Society.

Marion Parks, a member of our Museum staff more than twenty years ago, but connected with the American diplomatic service in Spain for many years since.

Mr. Phil Orr of the Santa Barbara Museum of Natural History, who doesn't visit us often enough.

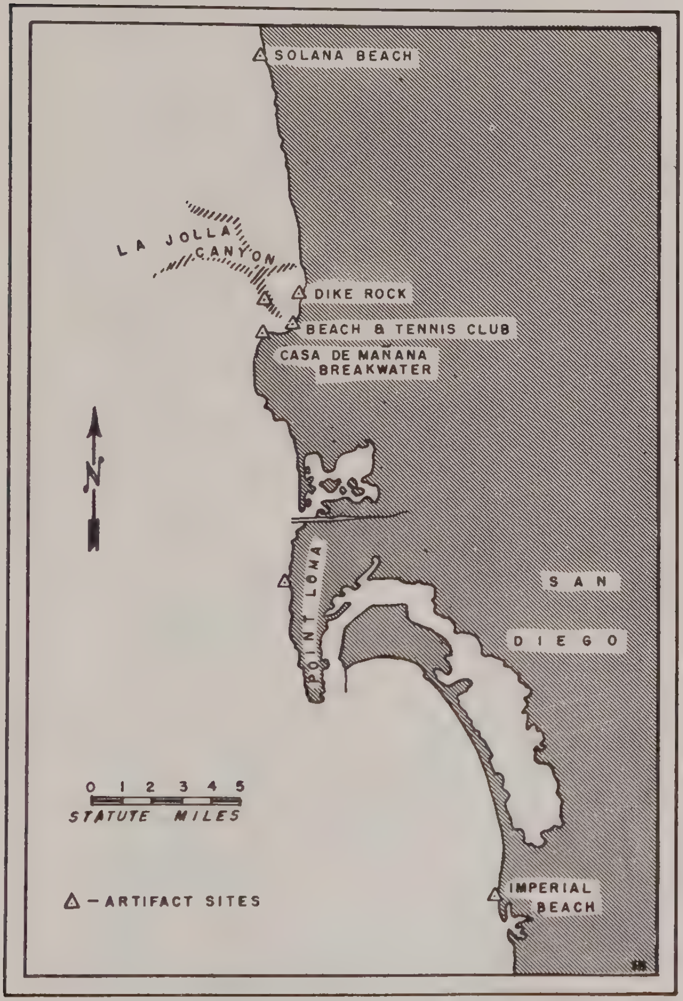
SOLANA BEACH
LA JOLLA CANYON
DIKE ROCK
BEACH & TENNIS CLUB
CASA DE MAÑANA BREAKWATER
N
POINT LOMA
SAN DIEGO
0 1 2 3 4 5
STATUTE MILES
△ – ARTIFACT SITES
IMPERIAL BEACH

FIG. 1—MAP OF THE COAST OF SAN DIEGO COUNTY SHOWING THE UNDERWATER SITES AND THE SUBMARINE CANYON OFF LA JOLLA

aqua lungs, or self-contained underwater breathing units, were sometimes used. These consist of a tank of compressed air carried on the diver's back, and a demand regulator and mouthpiece, and allow a swimmer complete freedom of movement under water, as there are no lines or hoses running to the surface. It is possible for a diver to work in shallow water for as long as two hours in one dive with these units, although the ocean temperatures here are generally too cold to allow comfortable submersion for that length of time, unless he be equipped with one of the new sponge-rubber suits.

At the Beach and Tennis Club site the mortars were found to occur among patches of cobbles from which the usual sand cover had been scoured away by the ocean currents. In a more or less seasonal cycle the cobbles are laid bare in the fall and winter, and covered with sand in the spring and summer.

One of the most frequently used methods of searching for the mortars was to cruise slowly over the area on a paddleboard, peering at the bottom through a face-mask or look-box until a mortar or a likely-looking patch of cobbles was found. Then the diver slipped over the side and swam to the bottom. A skiff with a partner to row it was sometimes used in lieu of the paddleboard.

The *San Diego Union* of June 29, 1952, carried a short feature article telling of the recovery of more than a hundred mortars from the water at Solana Beach by Warren Hamaker, a skin-diver. In size, shape, and material they are indistinguishable from those found at La Jolla.

Mortars have also been found singly or in small numbers at Dike Rock near Scripps Institution, off the Casa de Mañana breakwater, off Point Loma, and at Imperial Beach near the Mexican Border.

Within the last few months, Limbaugh, Rechnitzer, and Charles Fleming, also of Scripps Institution, have found a metate and two mortars on the edge of the submarine La Jolla Canyon in water about 100 feet deep and nearly half a mile from shore. The assumption is that there are probably more artifacts in this area and depth, but the fact that diving gear must be used precludes the possibility of much exploration of the bottom here. It is obvious that the shallower areas are the easiest to work, and that lack of time, equipment, and trained divers, as well as the immense area and poor visibility, will make the recovery of artifacts from deep water somewhat fortuitous. However, the unarguable point can be made that the artifacts do occur at this depth and distance from shore.

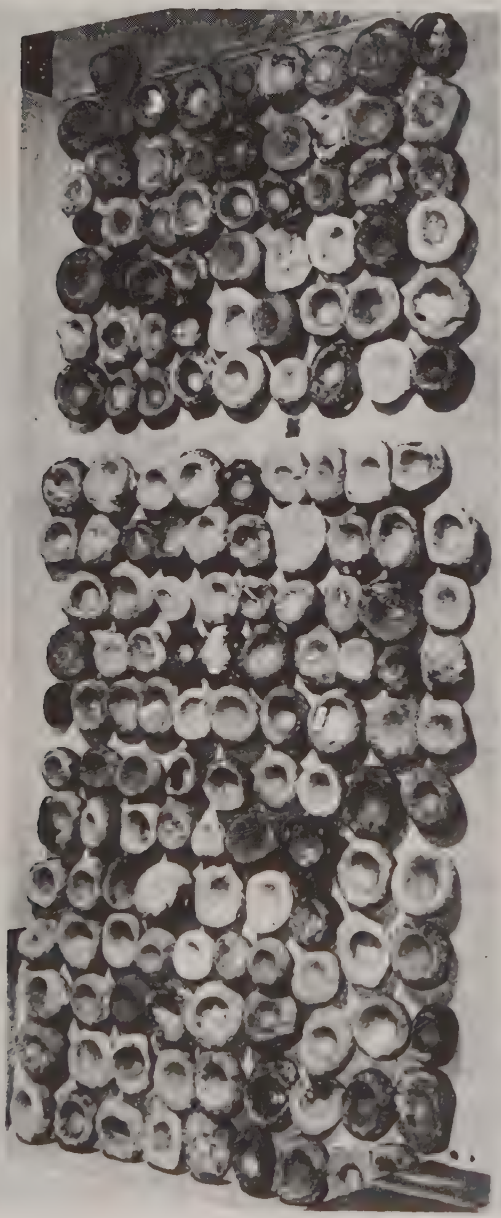

FIG. 2—PART OF THE MORTARS FROM THE BEACH AND TENNIS CLUB SITE AT LA JOLLA

The mortars run rather consistently to size, averaging about 8 inches in diameter. Most of them are made of sandstone, while a few are of granite, and the latter are almost invariably better finished, possibly owing to the greater hardness of the rock. Many of the sandstone mortars appear to have been made from a concretion in the sandstone bedrock, which was somewhat harder than the surrounding rock. The outside surfaces of the sandstone mortars often show large flaking scars as the result of rough shaping and the top edge or rim as well as the entire inner surface of the mortar opening is apt to show pecking marks. In fact, a few of the mortars show the pecking marks so distinctly that it is questionable if they were ever used as utilitarian implements. This factor may or may not be significant.

Archeological research in San Diego County coastal sites has been confined largely to surface surveys, with an occasional test pit or trench in some of the larger sites. It has been possible, however, to establish a chronology of three cultures beginning with the early San Dieguito. This was followed by two phases of the La Jolla Culture, which, in turn, was succeeded by the historic Diegueño Indians. The dating of the San Dieguito and La Jolla periods has not been too well established, and there is a distinct possibility that they are both much earlier than has been suspected heretofore.[1]

Small stone mortars of the type found underwater are known in both the La Jolla and later Diegueño cultures with no apparent variation in type. In fact, small stone mortars are known in practically all southern California Indian cultures except the very early ones. There must have been a grinding complex almost amounting to a compulsion to account for the large number of mortars found just in the La Jolla area in underwater sites. No such concentration of them has been found in digging, but this may reflect the paucity of excavation. There are the remains of a large site at La Jolla along the immediate coastline, but the chances of digging there are practically nil. The area is covered with an exclusive residential district and the property owners have an understandable aversion to having lawns, flower-beds, driveways, etc., torn up by eager persons wielding picks and shovels in the interests of science.

This site, known as W 1 (Beach and Tennis Club Area) in the San Diego Museum of Man survey records, is probably the inshore remnant of an inhabited area that extended seaward in

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[1] See George F. Carter for Interglacial Site at San Diego, California, *Masterkey*, Sept.-Oct., 1954.—Ed.

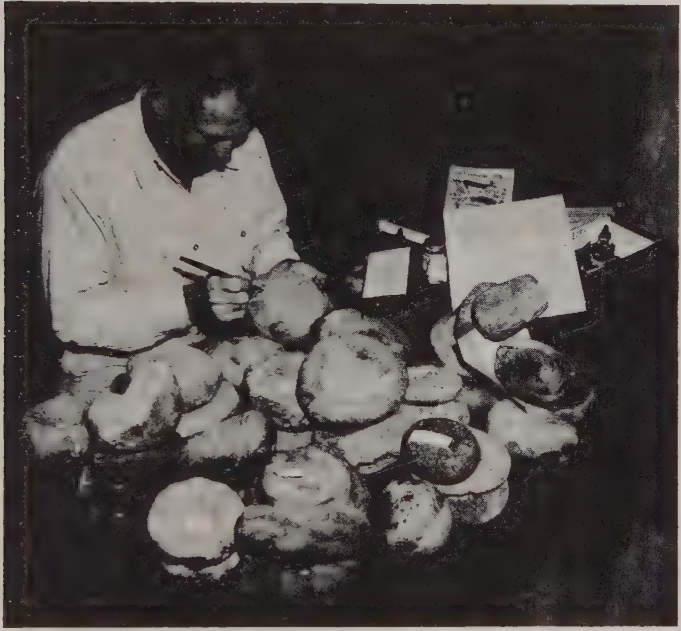

FIG. 3—ALLANSON CATALOGUING THE RESULTS OF ONE DAY'S DIVING

times past. Malcolm Rogers' notes written in 1925 mention finding artifacts in the crevices of an exposed off-shore reef at low tide, but the type of artifact is unfortunately not mentioned.

Mr. Alonzo de Jessop told of collecting mortars from this area as a small boy many years ago in company with his father, an enthusiastic collector of Indian artifacts. It is his belief that the mortars were eroding out of the top levels of the sea cliff on which the remains of W 1 are located, and he recalls that the favorite time for collecting them from the beach and shallow water was after the winter storms when the heavy surf had pounded and broken away portions of the cliff face.

Waterman,[2] Du Bois,[3] Sparkman,[4] and Boscana[5] all mention the use of small stone mortars during boys' initiation rites when toloache or an infusion of jimson weed (*Datura meteloides*) was drunk from the mortars by the initiates. When the large number of mortars was first found underwater, much thought was given to the possibility that these might be ceremonial sacrifices or offerings and that they had been thrown deliberately into the ocean, possibly as a propitiation. This idea was further strengthened by the fact that, with the exception of four metates, one mano, three net-weights, and two pestles designed for use in very large mortars, no other artifacts have been found. To date there is a complete dearth of chipped tools or small pestles to fit the mortars. Many scrapers, choppers, and pulping planes of both the Diegueño and La Jolla cultures are quite large and heavy, and would probably resist movement by wave-action quite as well as the mortars. The junior author, who has done most of the diving, is certainly skilled enough as an archeologist to recognize such tools, but in the many hours he has spent on the bottom, nothing in the line of chipped stone has come to light. The net-sinkers could have fallen accidentally from nets being set for fish by the Indians.

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[2] Waterman, T. T., 1910, p. 294, pl. 21.
[3] DuBois, C. G., 1908, p. 130.
[4] Sparkman, P. S., 1908, p. 207.
[5] Boscana, G., 1933, p. 135.

The deliberate sacrifice line of thought was rather reluctantly discarded, however, despite the fact that it offered an explanation for the presence of these objects on the ocean bottom.

It is becoming increasingly evident, we think, that we are dealing with a series of drowned early Indian sites, and three possible solutions offer themselves to account for the disappearance of habitation sites beneath the waves. The first is a rise in sea-level, the second a subsidence of the coast line, and the third is the erosion of the land by wave action.

No very significant changes in sea-level or the subsidence or rising of the land mass are known to have occurred in southern California in many hundreds of years, so unless we are willing to concede great antiquity for the mortars, neither of the first two hypotheses is tenable.

Coastal erosion seems to be the most plausible answer. Measurements of it have been made by Shepard and Grant[6] who found extremely rapid recession of the shorelines in certain areas and relative stability in others. Factors involved in the rate of retreat are the hardness of the rock, planes of structural weakness, coastal configuration, solubility of rocks and rock cement, height of cliffs, nature of wave attack, etc. The conclusions are that erosion has not been severe during the last few decades, although extensive erosion has taken place in the

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[6] Shepard, F. P., and U. S. Grant, IV, 1947, pp. 922-23, 926.

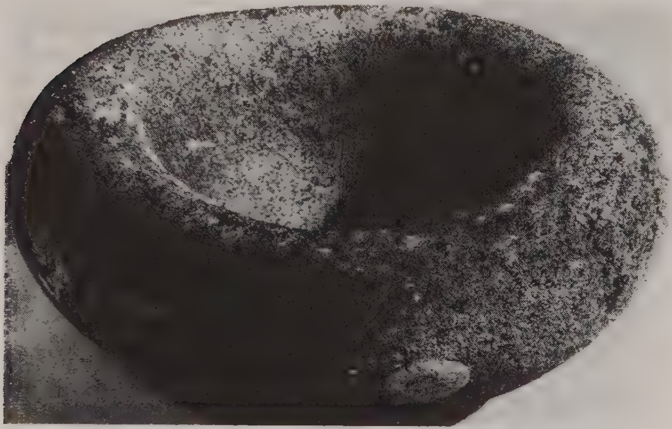

FIG. 4—ONE OF THE BETTER SHAPED MORTARS. (Diameter 6 in.)

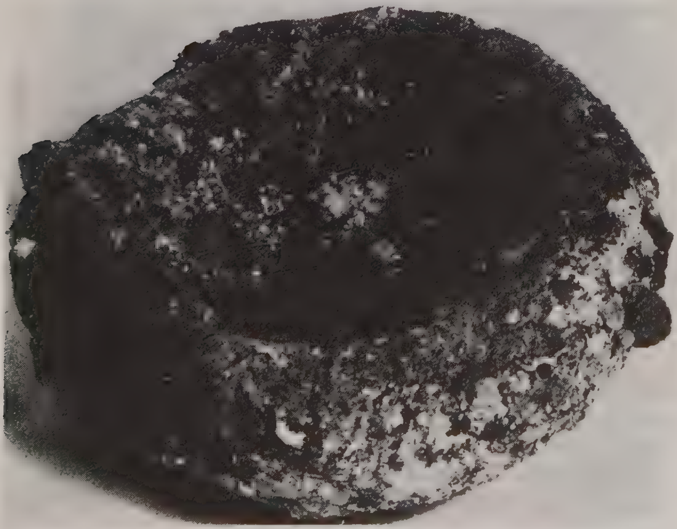

FIG. 5—A MORTAR FROM DEEP WATER SHOWING THE MARINE PLANT AND ANIMAL GROWTH THAT COVERED MANY OF THEM

last few thousand years, and that significant erosion has taken place on rare occasions.

Much of the present coastline at the Beach and Tennis Club site is protected from heavy surf by the shape and location of the underwater and offshore La Jolla Canyon (see map, fig. 1). This deep-water area near the coast breaks up the wave pattern resulting in low breakers at this point. The area is protected from storms from the south and southwest by a rocky headland that photographs[7] show to have changed little in forty years. Infrequent northwest storms cause a heavy surf to beat along this shore, and if we assume that the mortars 2000 feet from shore are at or near their original location, a very long period of erosion is indicated. The configuration of the present seacliff indicates a long extension of the land mass into an area now covered by the ocean.

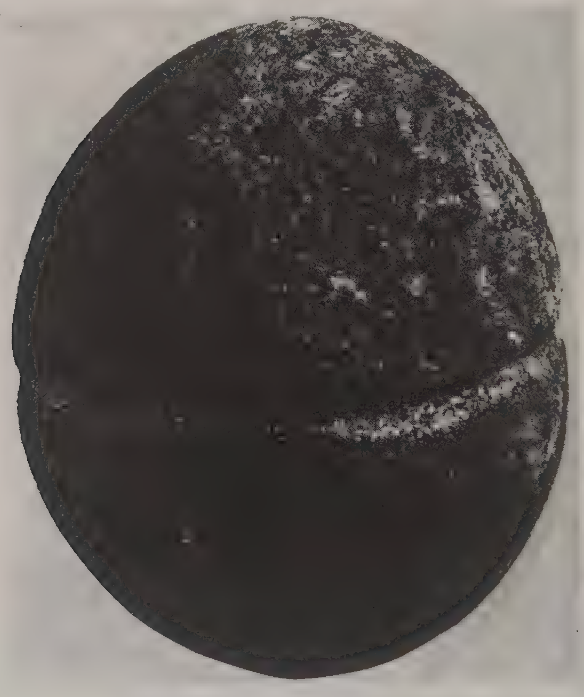

FIG. 6—ONE OF THE GROOVED NET-WEIGHTS FROM LA JOLLA
(Maximum diameter 3¾ in.)

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[7] Shepard and Grant, pl. 2 (3 and 4), p. 923.

The possibility that the mortars may have been moved by wave action from their original location must be considered, although it seems quite improbable as the exterior surfaces of the mortars show no signs of battering, a factor that would be concomitant with prolonged rolling in a surf zone. Furthermore, the soft nature of the sandstone from which most of the mortars were fashioned could not withstand any prolonged battering without disintegrating, and it may be significant that only three broken mortars have been found.

Another possibility is that the mortars have moved gradually, albeit slowly, seaward down the slope of the ocean floor as the water currents alternately piled up sand and scoured it away into deeper water. Such a movement, although cumulative, probably would not move the mortars very far.

Many of the mortars were covered with marine shells, especially in the opening or cup. These have been identified as *Ostrea lurida*, the native California oyster.[8] This bivalve is primarily an inhabitant of bays and protected waters, although it has been known to grow in the more exposed sections of the ocean.

If we presume an average coastal erosion of six inches a year, a seemingly excessive amount, we arrive at an age estimate of around 4000 years for the mortars found farthest from the present shore. This figure is considerably older than the present accepted chronology, which does not necessarily mean that it is wrong. It is thought that some of the Carbon 14 material now under examination will help to substantiate the earlier date.

This paper brings up a number of problems and can answer almost none of them. Why are so many mortars concentrated in two of the underwater sites? Why are no chipped stone tools found in conjunction with them? Why do the mortars show so little sign of surf-battering if these are drowned sites? How far have the ocean currents moved the mortars from their original locations? We arrive at no conclusions, but we do offer several hypotheses to explain the presence of the mortars on the ocean floor, all of which may be wrong.

The senior author, who can be reached at the Scripps Institution of Oceanography, La Jolla, California, is attempting to collect all the information available on underwater archeology, especially that on the west coast, and would appreciate any reports of such finds. To date, there are records of some 600 mortars. How many more will be found?

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[8] Ricketts, E. F., and J. Calvin, 1953, p. 162, pl. zzxv, fig. 81.

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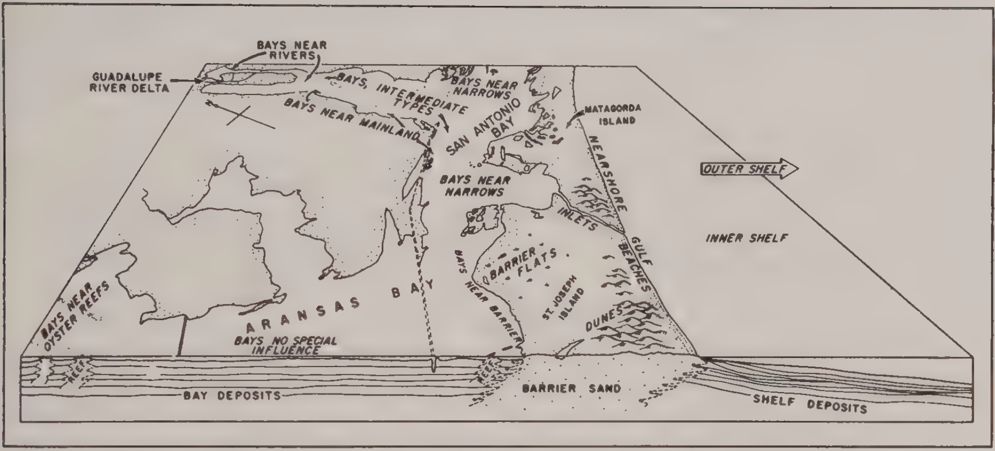
BAYS NEAR RIVERS
GUADALUPE RIVER DELTA
BAYS, INTERMEDIATE TYPES
BAYS NEAR NARROWS
BAYS NEAR MAINLAND
SAN ANTONIO BAY
MATAGORDA ISLAND
NEARSHORE
OUTER SHELF
BAYS NEAR NARROWS
INLETS
INNER SHELF
GULF BEACHES
BARRIER FLATS
BAYS NEAR BARRIER
ST. JOSEPH ISLAND
DUNES
BAYS NEAR OYSTER REEFS
ARANSAS BAY
BAYS NO SPECIAL INFLUENCE
REEF
REEF
BAY DEPOSITS
BARRIER SAND
SHELF DEPOSITS

Fig. 1—Block diagram showing the depositional environments of the area near Rockport, Tex.

This report on a current A.P.I. project outlines . . .

Stratigraphic Research That May Pay Off

by Francis P. Shepard

PROJECT 51 of the American Petroleum Institute has involved a study of the sedimentation conditions along the northern coast of the Gulf of Mexico. In initiating this work, operations were conducted along a central portion of the barrier island and embayed Texas coast, choosing the Rockport-Aransas Pass area where a minimum amount of industrial pollution has affected the bays.

The area includes San Antonio, Mesquite, and Aransas bays, along with St. Joseph and Matagorda Islands and the bordering Continental Shelf. A large part of the project has been devoted to making a detailed study of this area during the past 3½ years.

Most of the thousands of samples obtained in this work have now been quite completely studied. And they have been supplemented by a series of borings along the length of San Antonio Bay and out on the barrier islands. So we have more than a two-dimensional picture of the environment of deposition—a third dimension has been added so that the sediment units can be more clearly defined.

The study of these sediments has been somewhat unique since it has included a joint effort by sedimentationists, biologists (including students of macroorganisms, foraminifera, ostracods, microfossils, and bacteria), clay mineralogists, chemists, and—to a limited extent—petrographers and physical oceanographers.

This has been possible because of the wide diversity of oceanographic studies in progress at Scripps Institution and also because of the cooperation of several other universities in the project.

Geographic setting . . . The Rockport-Aransas Pass area of intense work is illustrated by the block diagram in Fig. 1.

The bays of the area are shallow. San Antonio Bay to the northeast has depths of only about 6 ft. at a maximum. Mesquite Bay has depths of only 4 ft. But Aransas Bay reaches depths of as much as 13 ft.

The combined drainage of the Guadalupe and San Antonio rivers enters at the head of San Antonio Bay and has resulted in the building of Guadalupe Delta. Smaller streams come indirectly into Copano Bay. Aransas and Mesquite bays, on the other hand, receive no drainage of any significance. So their sediments must have come

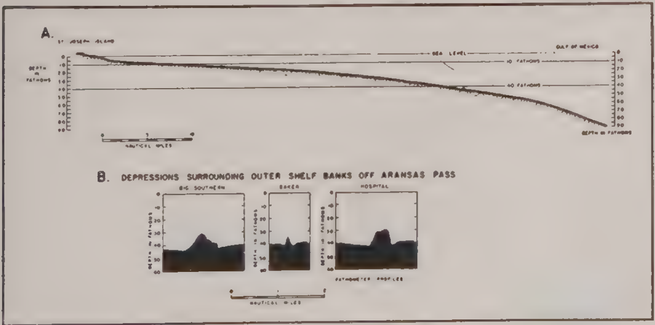

Fig. 2—The general profile of the Continental Shelf and the small banks which rise near the 40-fathom curve. The rise shown on the profile is much smaller than the banks.

Author is with Scripps Institution of Oceanography, University of California, La Jolla. Contribution from the Institution's New Series No. 752. This investigation was supported by a grant from the American Petroleum Institute, Project 51.

largely as transfer from other bays or from material carried over from the barrier islands by flood, blown in by wind, or carried in through the inlets which connect both of these bays with the gulf.

The barrier islands are very wide in this area, possibly the widest of any place in the world. They reach a maximum width of somewhat over 5 miles. The broad beaches on the gulf side are bordered by lines of dunes and so-called beach ridges. On the bay side of the barrier islands, there are extensive flats, some of which are cut by channels and lakes. Many of these lakes are circular.

These low inner borders may be referred to as "barrier flats." Some of them are apparently overwashes from the gulf side. Others are of less certain origin. The Continental Shelf extends out for 50 miles beyond the coast, ending at depths of 50 to 60 fathoms. The inner portion of the shelf has comparatively steep slopes down to about 5 fathoms. Then it slopes very gently out to 20 fathoms, beyond which there is a slight steepening. In general, the Continental Shelf is quite even, although it has very slight irregularities and some hills rise abruptly from the outer part of the shelf near the 40-fathom line (Fig. 2).

Bay sedimentary environments . . . In the shallow bays of the area, there appear to be a number of very distinctive influences which serve to differentiate the sediments. Thus, we have the influence of the Guadalupe River at the head of San Antonio Bay which brings into the bay a considerable quantity of plant or wood fibers along with ferruginous aggregates which are mixed with the other sediments. The fresh water introduced by the river results in a high production of ostracods so that they actually exceed the foraminifera in abundance in many samples of this environment.

Clay makes up a very high percentage of the deposits in the bay near the river mouths and also on the Guadalupe Delta. This clay is unusually high in calcium carbonate, introduced as particulate material. It presumably comes from the Austin chalk and from various Lower Cretaceous and Paleozoic formations.

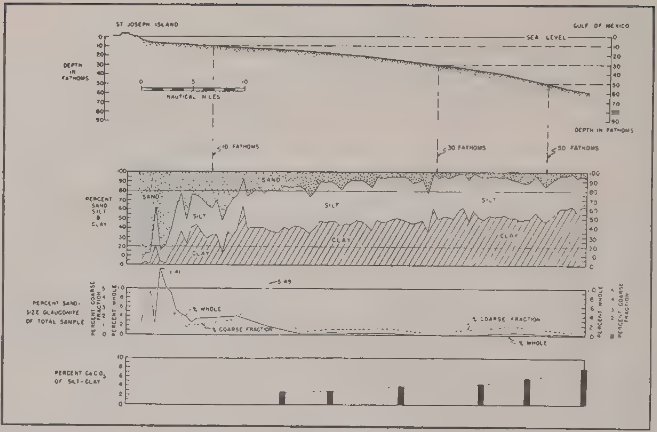

Fig. 4—Variation of sediments in a line crossing the Continental Shelf off the Rockport, Tex., area.

Lower down in the bays, the plant materials become scarce and the ostracods are greatly exceeded by the foraminifera in the coarse fraction (greater than $\frac{1}{16}$ mm.). The clay content remains high, considerably exceeding the silt, and the sand content is low. Locally in these intermediate portions of the bays, oyster reefs are present with a resulting high shell content. Some of this shell material is transported away from the reefs and thus influences the sediment in the vicinity.

The southeastern side of San Antonio Bay, all of Mesquite Bay, and the southwestern side of Aransas Bay—all show the influence of nearby inlets or narrows. The effect of these constricted zones is to develop currents capable of transporting sand. Thus the sand becomes more abundant in these areas than clay. Silt, on the other hand, remains relatively low so that the typical sediments of "bays near narrows" are clayey-sands.

The deeper part of Aransas Bay—where the influence of the river is very indirect, where the inlet influence is insignificant, and where the depth of water allows more permanent settling of the fines—has a clayey sediment in which there is a surprisingly high content of foraminifera tests. This unusual abundance is probably a result of the slow rate of accumulation of clastic sediments. In looking at sievings of the coarse fractions of samples from this "bay no special influence" environment, we have commonly found that the ½-¼ and ¼-⅛ mm. fractions are predominantly foraminifera, sometimes constituting as much as 90 per cent. A correspondingly small percentage is found of terrigenous minerals such as quartz and feldspar. Thus these various bay environments result in deposits which are quite distinctive in character.

Barrier island sedimentary environments . . . As we've seen, the barrier islands have several distinct zones. Most

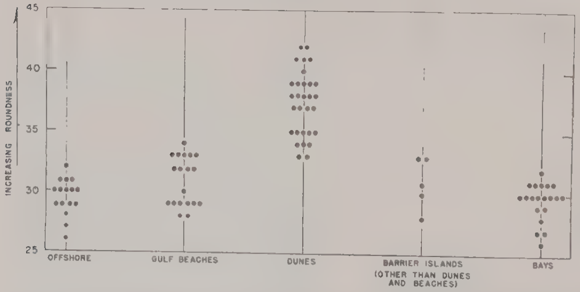

Fig. 3—The coefficient of roundness related to barrier island and nearshore environments.

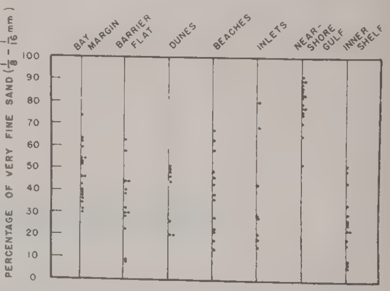

Fig. 5—The percentage of very fine sand in sediments from the barrier islands and nearby environments.

of the island sediments are high in sand content and the beaches and dunes have very little else besides sand material. The best method which we have found for differentiating beach and dune sands is by a study of the roundness.

To do this, we take the ⅛-1/16 mm. sieving and classify 100 grains according to the scale presented by Powers (1953). Almost all of the dune sands in the area are more rounded than the beach sands or the sands from other environments (Fig. 3). The swamp areas inside the dunes have a fairly large amount of silt and clay. So they are more comparable to some of the bay sediments. They differ from them in having mineral aggregates, partly due to evaporation when the flats dry during a protracted time of low sea level. The sediments have more wood fibers and more pollen and spores than the portions of the bays which have an equally high sand content.

The inlets which connect the open gulf to the bays are high in sand, but they contain an appreciable amount of echinoids carried in from the open gulf. The faunas are a mixture of gulf and bay types. The present inlets are small in area at the present time, but much of the barrier-island material may have been made by the filling of old inlets. So the environment may be very important.

Continental Shelf deposits . . . The shelf sediments have one very distinct boundary and another that is more gradational. The sharp break occurs between the sandy sediments, extending out about 1 mile from the coast to about 30 ft. of water, and the sand-silt-clay materials farther out. In one line of very closely spaced samples (Fig. 4), the sediment had a rather sharp break in grain size at the foot of the inner slope and then a more gradational change at greater distances out from shore. This is not true of other profiles, however, particularly of those to the north. The sandy sediments near shore could easily be confused either with the beach sands or with sandy sediments of the barrier flats and inlets.

However, there is one very distinct difference. It is found that the "nearshore gulf" sediments are heavily weighted in the ⅛-1/16 mm. grain size, commonly about 80 per cent, which is quite different from the other environments (Fig. 5). Glauconite is also important in this environment so that the samples differ in this respect from the equally sandy sediments on the inside of the barrier islands and along the bay margins where glauconite is rare.

Inner shelf . . . The "inner shelf," beginning where the sand decreases beyond the nearshore gulf, is given a somewhat arbitrary outer boundary at the 20-fathom curve. This is because the foraminifera are predominantly pelagic beyond 20 fathoms, whereas pelagic foraminifera are scarce inside the 20-fathom line. The sediment of the inner shelf is a mixture of sand, silt, and clay in about equal proportions. The material differs in various respects from the fine sediments of the bays. The silt content is normally considerably higher than in the bay sediments.

Outer shelf . . . The sediments of the "outer shelf" are variable in the area. The clay content is high and sand low directly off St. Joseph Island (Fig. 4), but sand is fairly abundant to the north. In the zone of fine sediments off Aransas Pass, the most notable feature is that the coarse fraction (greater than 1/16 mm.) consists to a very large extent of foraminifera. Terrigenous sands (which are principally quartz in this area) are very scarce. Glauconite makes up a smaller fraction, but it can still be recognized in most samples and serves to differentiate these sediments from those found in bays.

To the north, the outer shelf sediments are much closer in character to those of the inner shelf. Terrigenous sands and mollusc shells are abundant, so there is a large coarse fraction and glauconite continues seaward as an important constituent. The foraminifera are less important here than on the outer shelf to the south. The submerged hills on the outer shelf (Fig. 2) apparently are covered with shells and coralline types of deposits. It is notable that these hills have a slight ring depression virtually surrounding them.

Third dimensional aspects of the sediments . . . A series of borings were made in the area using light drilling equipment mounted on a barge in the bays and on a truck during work on the islands and on the Guadalupe Delta. These borings attained an average depth of 55 ft. They were supplemented by borings of 20 to 40 ft. in depth made by a hand-operated Porter soil sampler.

The borings along the Guadalupe Delta and along the length of San Antonio Bay have mostly extended down to the base of the Recent or to sediments indicating another cycle of deposition. This base can be determined either by the occurrence of the oxidized Beaumont clay, of presumable Pleistocene age, or a river deposit which was high in plant fibers and devoid of all signs of bay deposition. Above this contact, the deposits differed very little from those being formed at the present day.

The exception was found in the case of the Guadalupe Delta where the borings showed that true delta deposits give out at a depth of 5 to 10 ft. They are underlain by bay deposits which indicate nearness to a river mouth.

With greater depth in the holes, the bay deposits showed less and less influence of the nearby rivers. In three of the holes, great thicknesses of oyster-reef material were encountered, indicating that deposition occurred in conditions not greatly different from the present day. In one hole, near the lower end of the bay, a maximum of about 80 ft. was bored before encountering the deposits of an older cycle.

Under the barrier islands, sandy sediments generally continue for considerable depths—especially in the borings made on the barrier beaches. At one place these sands continued with very little change in character down to about 60 ft. On the bay side of the barrier islands, however, the sediments encountered on top appear to be characteristic of inlets or barrier flats. Underneath, in some cases, they suggest bay environments.

Seaward of the barrier islands, both Humble Oil Co. and Gulf Oil Co. have obtained samples from above the Pleistocene. These were kindly supplied to A.P.I. Project 51. We have found from a preliminary study that the Recent offshore deposits do not extend very far below the bottom. They terminate at about 10 ft. in a well 3 miles seaward of St. Joseph Island. And they are underlain by a considerable thickness of barrier island deposits. Nine miles seaward of Mustang Island, on the other hand, the shelf deposits may be 60 ft. thick and are underlain by both barrier island and bay deposits.

Summary . . . The information given above is only a brief outline of the material which has been gathered in 3½ years of A.P.I. Project 51. It does not discuss some of the special studies that have been made, particularly those already published. The information presented indicates quite clearly that the sedimentary environments in this Central Texas area have very distinctive sediments and the data give good promise that criteria of the type discussed can be used to distinguish between bay, barrier island, and Continental Shelf deposits. Distinguishing the other more specialized environments may also be possible in many cases. The criteria will be tested by comparison of sediments from other areas along the Gulf Coast.

The third-dimensional studies in the Rockport-Aransas Pass area indicate that present-day conditions were in existence during deposition of formations down to a considerable depth, especially in the bays and on the barrier islands. Indications coming from Carbon-14 age determinations (provided us by Magnolia Petroleum Co.) make it probable that the barrier islands and the accompanying bay deposits have grown up along with the rise of sea level at the end of the Pleistocene. In this way thick sand deposits developed under what are now the barrier islands and these sand lenses have become flanked with fine-grained materials which may produce future stratigraphic traps for petroleum.

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REPRINT FROM
CALIFORNIA FISH and GAME
"CONSERVATION OF WILDLIFE THROUGH EDUCATION"
VOLUME 41 JANUARY, 1955 NUMBER 1

EXPLORATORY OCEANOGRAPHIC OBSERVATIONS IN THE EASTERN TROPICAL PACIFIC, JANUARY TO MARCH, 1953[1]

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Scripps Institution of Oceanography of the University of California
La Jolla, California

Experimental fishing with Japanese "longline" gear by the Pacific Oceanic Fishery Investigations of the United States Fish and Wildlife Service has demonstrated the presence of deep-living yellowfin and bigeye tuna in the central equatorial Pacific (Murphy and Shomura, 1952). An imaginative oceanographic program carried on in conjunction with the experimental fishing has led to a reasonable oceanographic interpretation of the observed distribution of tuna (Cromwell, 1953).

Since nothing was known about the distribution of such deep-living tuna in the eastern equatorial Pacific, an exploratory expedition was sent out aboard the M. V. N. B. SCOFIELD from January 23 to March 18, 1953, under the joint sponsorship of the California Department of Fish and Game, the Inter-American Tropical Tuna Commission, and the Scripps Institution of Oceanography of the University of California. Biological results of this expedition were described by Wilson and Shimada (1955). In addition to the experimental fishing and the biological program, a limited oceanographic program was carried out. The purpose of this paper is to discuss the oceanographic results of this expedition.

OCEANOGRAPHIC OBSERVATIONS

The track of the M. V. N. B. SCOFIELD is shown in Figure 1. Due to failure of the bathythermograph winch, bathythermograph observations (to 900 feet) were made only at the 26 stations where experimental fishing was carried on. In addition, numerous observations of surface temperature (bucket thermometer) and surface salinity (Knudsen titration) were made. Figures 2 and 3 show the locations of these observations. At all stations except Nos. 25 and 26, surface samples were collected and frozen for subsequent analysis for dissolved inorganic phosphate-phosphorus and silicate-silicon. These analyses were made at the Scripps Institution by Mr. Robert Holmes, using standard absorptiometric methods.

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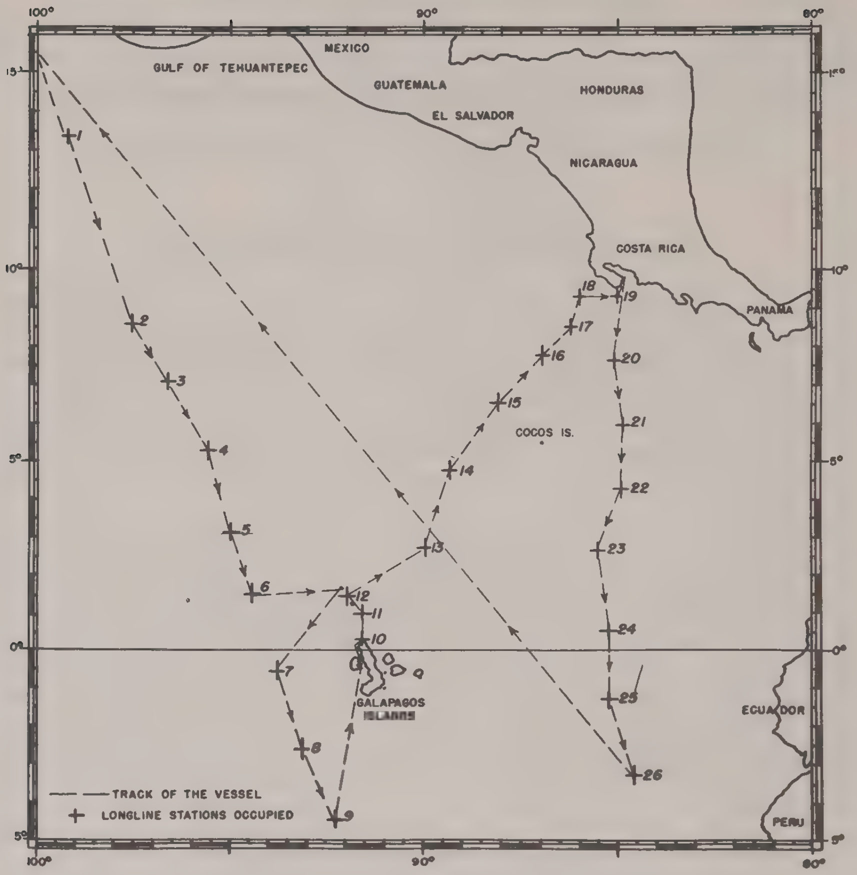
[1] Submitted for publication September, 1954. Contributions from the Scripps Institution of Oceanography, New Series, No. 753. This work was supported by the Office of Naval Research. Reproduced, by permission


100°
90°
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15°
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MEXICO
GULF OF TEHUANTEPEC
GUATEMALA
EL SALVADOR
HONDURAS
NICARAGUA
COSTA RICA
PANAMA
COCOS IS.
GALAPAGOS ISLANDS
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TRACK OF THE VESSEL
LONGLINE STATIONS OCCUPIED

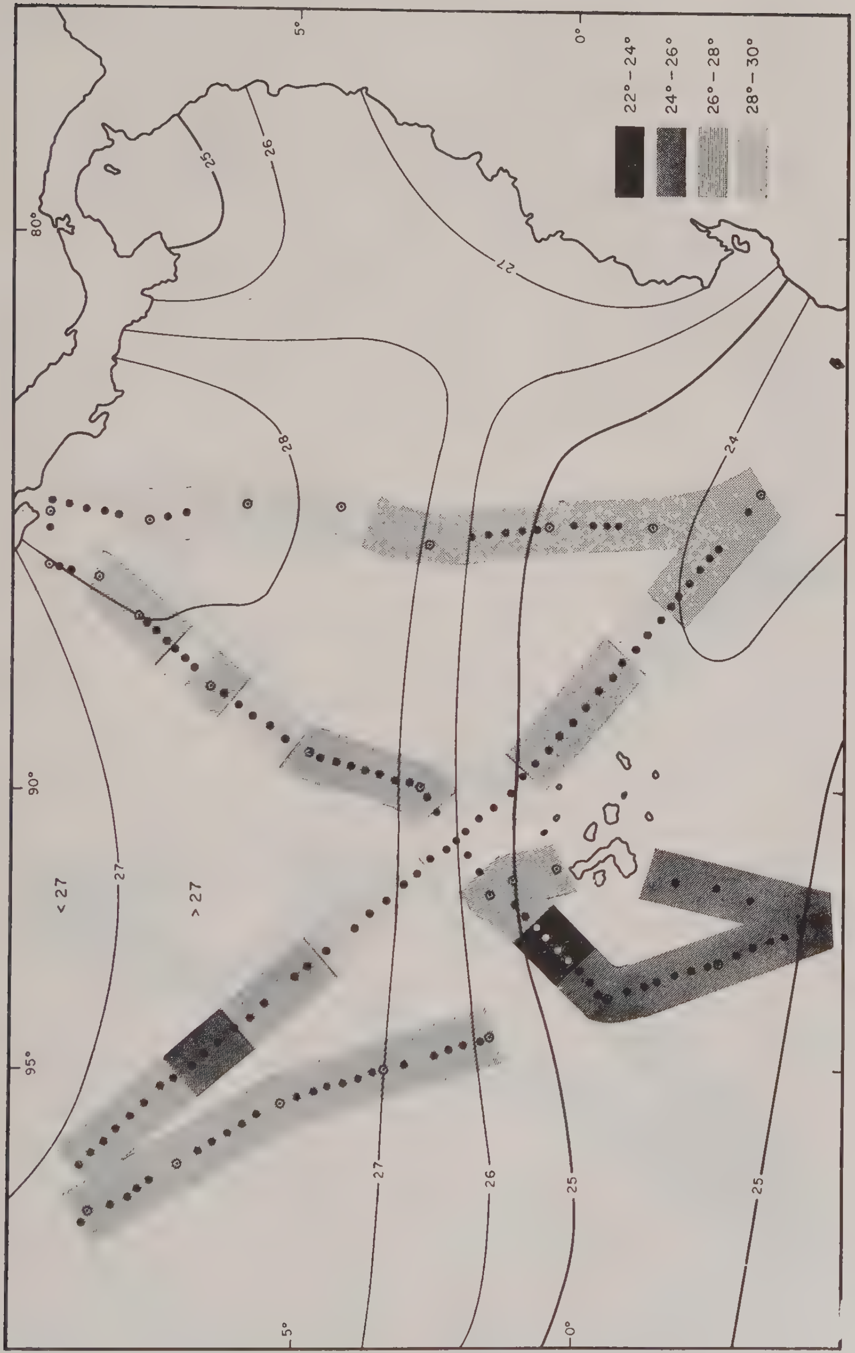
FIGURE 1. Track of M.V. *N. B. Scofield,* January 23 to March 18, 1953, showing location of experimental fishing stations.

In addition, current measurements were made, using towed electrodes (Von Arx, 1950) and a confined current drag from the drifting ship (Vine, Knauss, and Volkmann, 1954). Interpretation of the results of these measurements awaits completion of a theoretical treatment of such data now under way, and will be discussed in a subsequent paper.

DISTRIBUTION OF TEMPERATURE AND SALINITY

The horizontal distribution of surface temperature is shown in Figure 2 and of surface salinity in Figure 3. The distribution of temperature is also shown in bathythermograph sections, Figures 4, 5, and 6.

It was not considered advisable to attempt to contour surface distributions because of the spacing of observations, and because changes


5°
0°
80°
90°
95°
5°
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22° – 24°
24° – 26°
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28° – 30°
25
26
27
28
24
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25
25
< 27
27
> 27

FIGURE 2. Distribution of surface temperatures (Centrigrade) along track. Isotherms are February average surface temperatures, from Schott (1935).

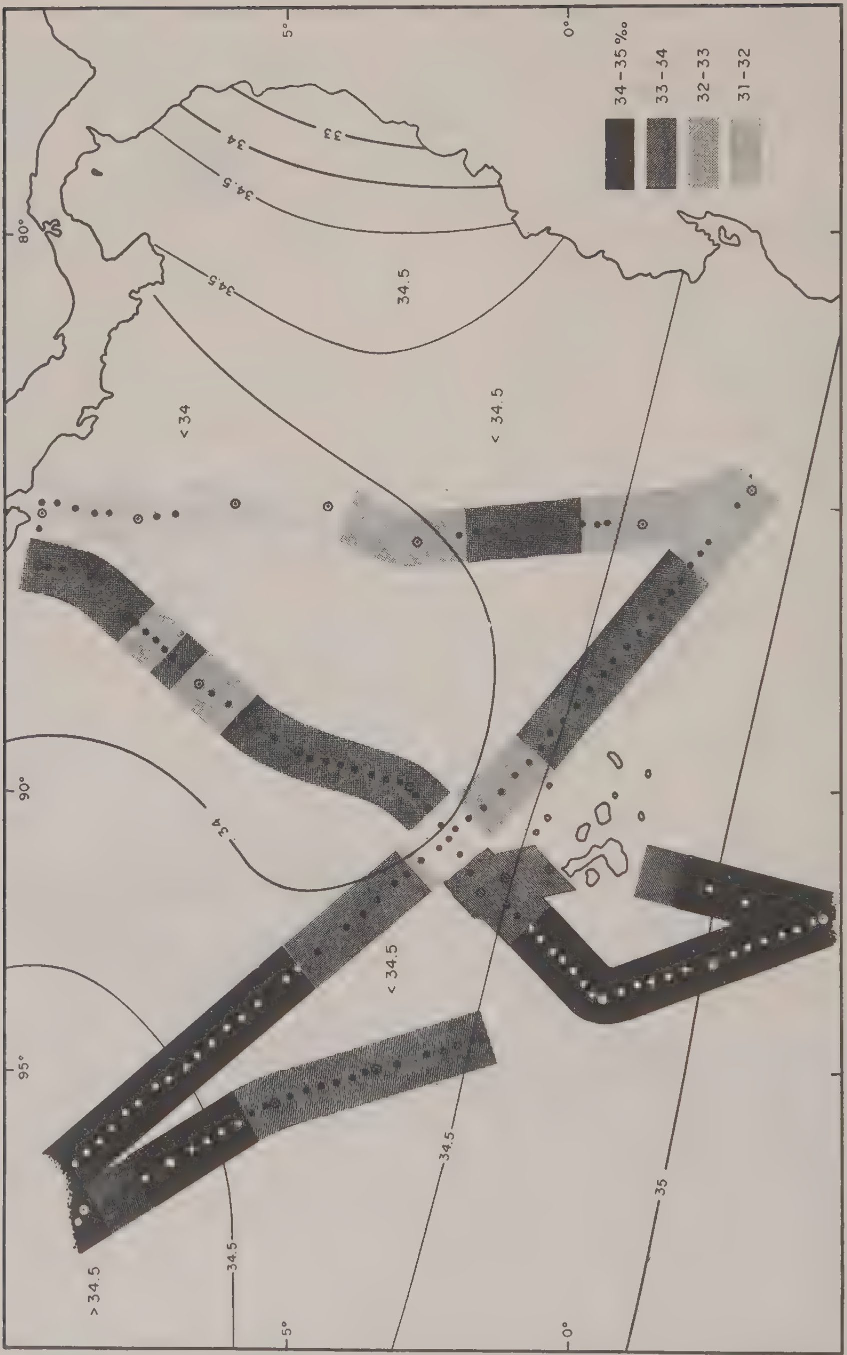
5°
0°
34–35‰
33–34
32–33
31–32
33
34
34.5
34.5
34.5
80°
< 34
< 34.5
90°
34
95°
< 34.5
34.5
35
> 34.5
34.5
5°
0°

FIGURE 3. Distribution of surface salinity along track. Isohalines are Northern Hemisphere winter average surface salinities, from Schott (1935).

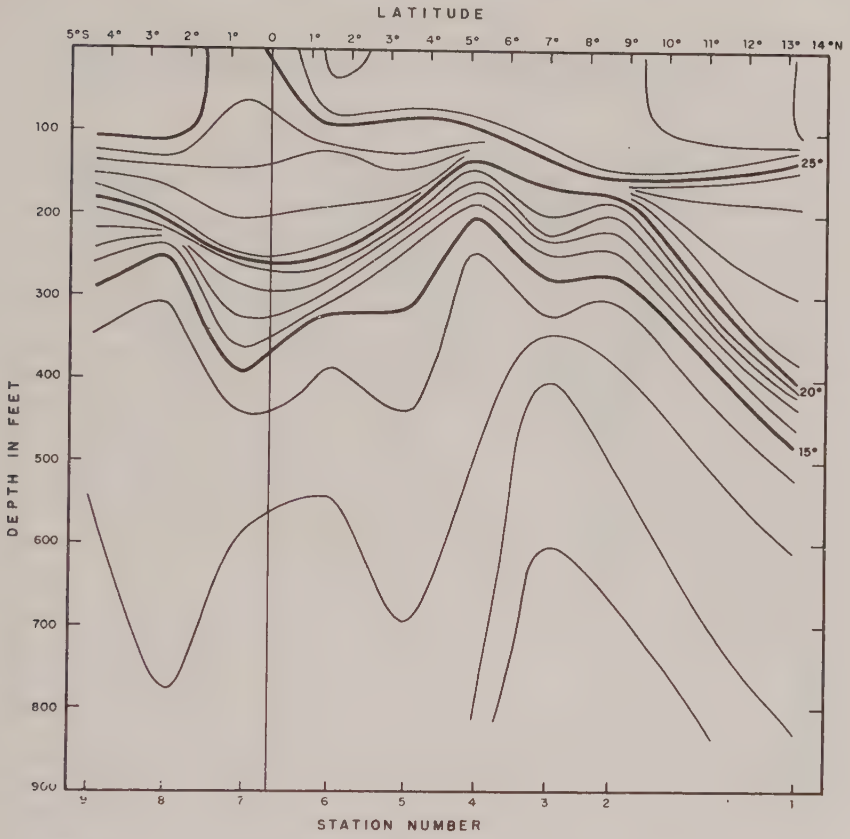

FIGURE 4. Temperature-depth section from westernmost bathythermograph profile.

in surface conditions during the cruise made it impossible to treat the data as simultaneous. Therefore, a system of shading was used to show variations in surface concentration along the track of the ship. The isopleths drawn on Figures 2 and 3 were taken from Schott (1935) and are intended to represent average surface temperatures in the month of February (Figure 2) and average surface salinity during Northern Hemisphere winter (Figure 3).

Examination of Figure 2 reveals a distribution of temperature on the westernmost line similar to average conditions. In particular, the relatively cold water found at the equator and south of the equator is consistent with the usual westward extension of cold water from the Peru Current which feeds the South Equatorial Current, and with upwelling at the equator due to wind-induced divergence (Yoshida, Mao, and Horrer, 1953; Cromwell, 1953). The coldest temperature observed, 23.5 degrees C., was located at zero degrees 30 minutes north latitude.

On the easternmost line, surface temperatures are strikingly different from the average values. Surface water with a temperature of greater than 28 degrees C. was found farther south and west than usual, and

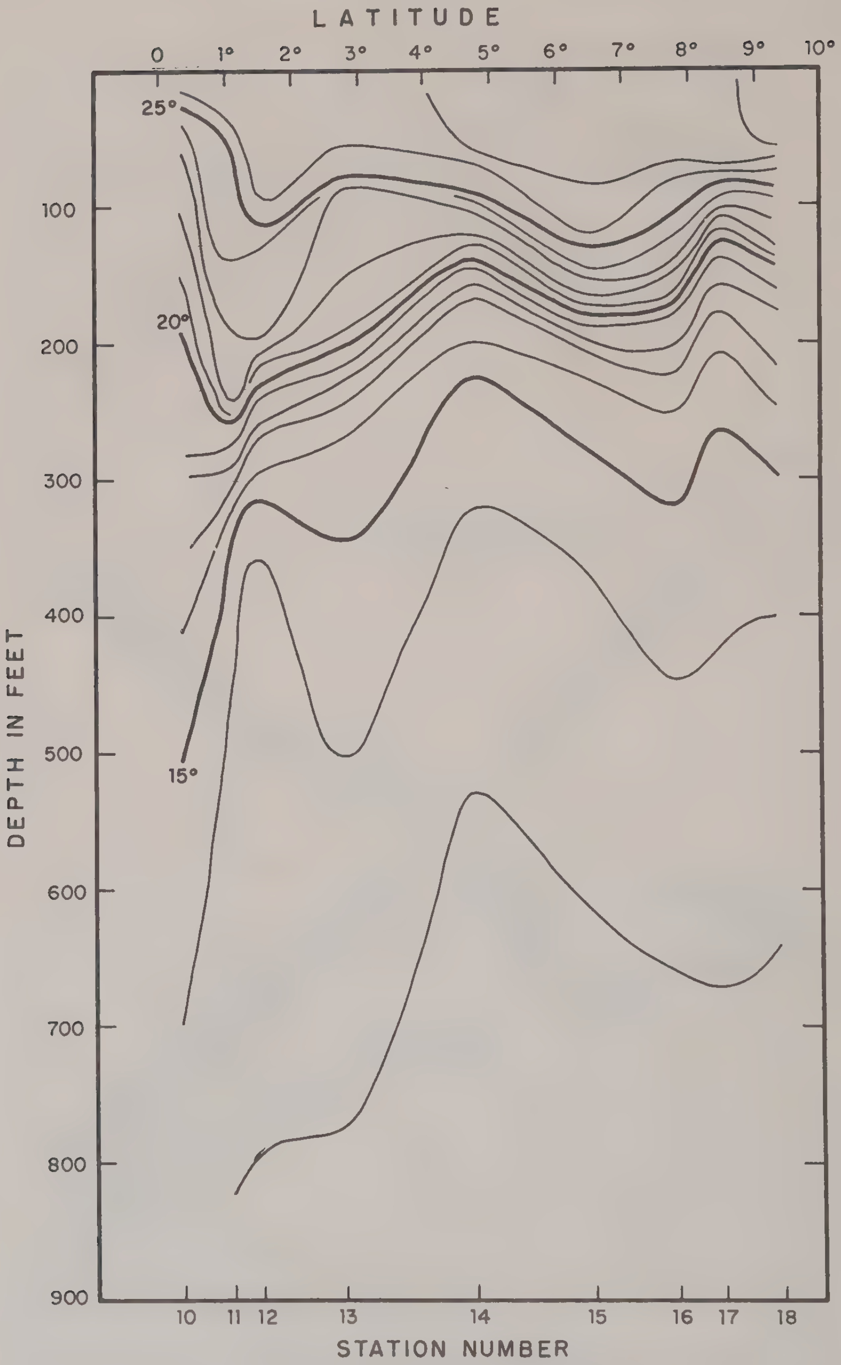

FIGURE 5. Temperature-depth section from central bathythermograph profile.

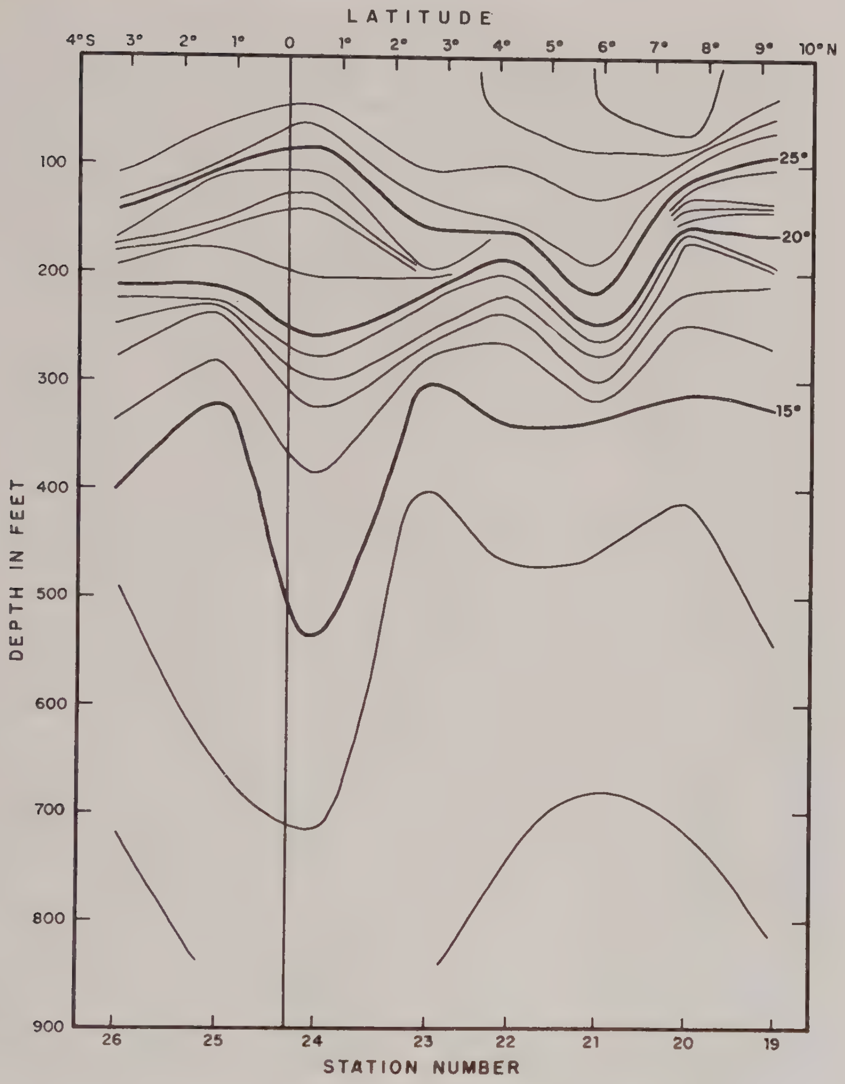

FIGURE 6. Temperature-depth section from easternmost bathythermograph profile.

in the region between Ecuador and the Galapagos Islands where February surface temperatures are usually less than 25 degrees C., values of 26 degrees to greater than 28 degrees C. were observed. Evidence of a rapid change in surface conditions is found in the region north of the Galapagos Islands, where an early line was recrossed less than three weeks later. On the later crossing, surface temperatures in the area were found to be 2 degrees C. higher than those previously observed. For example, on February 16, at 2° 07′ N., 90° 54′ W., the surface temperature was 26.4 degrees C.; on March 7, at 2° 00′ N., 90° 44′ W., the surface temperature was 28.4 degrees C.

Examination of the westernmost bathythermograph section (Figure 4) confirms the presence of upwelling at the equator, apparently from a depth no greater than 50 meters, in contrast with the central equatorial Pacific, where Cromwell's diagrams suggest that upwelling may be effective to depths as great as 100-150 meters. Unpublished observations from Scripps Institution's ''Shellback'' expedition, May to August, 1952 (Wooster, 1952) also show equatorial upwelling in the eastern equatorial Pacific to be effective to a lesser depth than in the central equatorial Pacific. However, since the depth of the thermocline in the equatorial region decreases from west to east (Sverdrup, Johnson, and Fleming, 1942; p. 708), shallow upwelling in the east may well be effective in supplying the photic zone with nutrients.

A trough in isotherms at the equator, below the depth of influence of upwelling, can be seen in Figure 4. This feature is also apparent in Cromwell's meridional sections and is probably related to the Equatorial Undercurrent, recently discovered through direct measurements of subsurface currents at the equator (Cromwell, Montgomery, and Stroup, 1954).

Conclusions concerning zonal flow can be reached from a meridional bathythermograph section only if the geostrophic approximation is valid, if the observations are sufficiently deep to reach a suitable reference surface, and if the relation between temperature and salinity is known (LaFond, 1949). Although the available observations do not entirely satisfy these restrictions, they are consistent with a westward North Equatorial Current north of 5° N. and with an eastward Equatorial Countercurrent south of 5° N. The southward extent of the countercurrent is indeterminate because of the failure of the geostrophic approximation in the vicinity of the equator.

The southern end of the central section (Figure 5) is complicated by the proximity of the southernmost station (Station 10) both to the equator and to the northern tip of Isabela Island, the largest of the Galápagos group. The Equatorial Countercurrent again appears to be present south of 5° N.; to the north the nature of the zonal flow is not obvious.

The easternmost section (Figure 6) shows no clear evidence of equatorial upwelling at the surface (see also Figure 2), water warmer than 27 degrees C. extending across the equator to the southernmost station, at 3° 16′ S. Below the surface a crest in isotherms can be seen, and deeper still the trough believed to be associated with the Equatorial Undercurrent.

Examination of the distribution of surface salinity (Figure 3) shows conditions to be most nearly average on the westernmost line, although values north of the equator seem to be several tenths per mille too low. The highest value, 34.74 °/₀₀ was found at 0° 42′ N. On the easternmost line conditions differ strikingly from average, with values of 31-32 °/₀₀ in the north (where average values are 33.5-34 °/₀₀) and values of 32-33 °/₀₀ in the south (where average values are 34.5-35 °/₀₀). In the region north of the Galápagos Islands where lines cross, the salinity decreased markedly during the three-week interval. Thus on February 16, at 2° 07′ N., 90° 54′ W., surface salinity was 33.34 °/₀₀; on March 7, at 2° 00′ N., 90° 44′ W., surface salinity was 32.28 °/₀₀.

DISCUSSION

The available observations are obviously inadequate, both in kind and in spatial coverage, for a clear understanding of the oceanography of the region. For example, it is not possible to draw adequate surface or subsurface horizontal distributions or to make velocity or transport computations. However, despite the limitations of the data, certain oceanographic features are clearly evident.

The equatorial divergence is a well-known phenomenon in the Pacific (Sverdrup, Johnson, and Fleming, 1942; p. 711). The presence during this cruise of equatorial upwelling in the westernmost section is apparent from examination of Figures 2, 3 and 4. It is confirmed by the results of phosphate and silicate analyses. An examination of Table 1 shows that the highest surface concentrations of phosphate were found at Stations 7 and 10, the two stations closest to the equator west of 90° W. (Relatively high values were also found at Stations 8 and 9, south of the equator in the South Equatorial Current; significantly lower concentrations were measured at all other stations). Concentrations of surface silicate were so low at all stations as to be at the extreme limit of sensitivity of the analytical method used, and hence are not tabulated here. However, the two highest values were again found at Stations 7 and 10.

Since data from the westernmost section seem to agree with average conditions, it is of interest to compare the relationship between oceanographic conditions and biological activity with that found in the central equatorial Pacific. Investigators there (King and Demond, 1953) report the greatest abundance of zooplankton in the region of the equator, the rich zone extending from about 6° N. to 5° S. latitude. Frequently, but not always, the zooplankton maximum occurred at or very near the site of upwelling. A statistically significant positive correlation was found between zooplankton volume and surface inorganic phosphate. Although, paradoxically, Wilson and Shimada (1955; Table 2) report the lowest plankton catches at the two stations with the highest surface phosphate concentrations, in general the same zone has a high standing crop of zooplankton. The catch of tuna in the eastern tropical Pacific (Wilson and Shimada, 1955; Table 1) shows peaks of over six tuna per 100 hooks at Stations 5 (3°06′N.) and 9 (4°28′S.), with good catches in between, and resembles, both in quantity and in meridional variation, certain of the central equatorial Pacific fishing sections (Murphy and Shomura, 1953). Thus, in general the relation between oceanographic conditions and biological activity is similar in the two areas.

The absence of surface indications of equatorial upwelling in the easternmost section is shown by Figures 2, 3 and 6. In addition, neither the surface phosphate nor the surface silicate concentrations were significantly higher at Station 24 than at the stations to the north. Unpublished data from the ''Shellback'' expedition, which established a series of oceanographic stations along 85° W. from 15° S. to 10° N. in July, 1952, also show no signs of upwelling at the equator. It is not surprising that sections across the equator within 300 miles of the eastern border of the Pacific do not show the usual picture of equatorial circulation found in the open ocean. The distribution of properties

TABLE 1

Surface Phosphate-phosphorus Concentrations, in Microgram Atoms Per Liter of PO_4-P, in Samples Collected by M.V. N. B. SCOFIELD, January to March, 1953

Station No.	Location	PO_4–P	Station No.	Location	PO_4–P
1	13° 18′ N.-99° 07′ W.	0.36	13	2° 47′ N.-89° 57′ W.	0.38
2	8° 35′ N.-97° 32′ W.	0.42	14	4° 46′ N.-89° 20′ W.	0.39
3	7° 02′ N.-96° 39′ W.	0.46	15	6° 32′ N.-88° 08′ W.	0.37
4	5° 12′ N.-95° 36′ W.	0.37	16	7° 48′ N.-86° 56′ W.	0.35
5	3° 06′ N.-95° 00′ W.	0.38	17	8° 29′ N.-86° 12′ W.	0.34
6	1° 30′ N.-94° 25′ W.	0.32	18	9° 22′ N.-86° 01′ W.	0.36
7	0° 36′ S.-93° 44′ W.	0.68	19	9° 20′ N.-85° 00′ W.	0.36
8	2° 36′ S.-93° 05′ W.	0.63	20	7° 36′ N.-85° 09′ W.	0.29
9	4° 28′ S.-92° 16′ W.	0.51	21	5° 54′ N.-84° 52′ W.	0.29
10	0° 20′ N.-91° 23′ W.	0.81	22	4° 14′ N.-84° 55′ W.	0.31
11	1° 06′ N.-91° 35′ W.	0.39	23	2° 40′ N.-85° 33′ W.	0.34
12	1° 32′ N.-91° 50′ W.	0.39	24	0° 32′ N.-85° 16′ W.	0.38

in this region is dominated by the proximity of the northern boundary of the Peru Current to the equator and by the effect of changes in local winds from season to season and from year to year on the location of this boundary and on the circulation north of the boundary.

There is ample evidence that 1953 was an unusual year in the eastern tropical Pacific. The presence of warm, low saline water between the Galápagos Islands and Ecuador is undoubtedly related to the displacement of the Equatorial Countercurrent southward along the coast of northern Peru, reported by Schweigger (1953). Surface temperatures of 28 degrees C. were observed as far south as Talara, Peru, in March, and animals whose normal habitat is northwest of Cabo Blanco, Peru, were found as far south as 11 degrees S. Between March 10th and May 25th, the 1953 Yale Expedition made oceanographic observations along the coast of Peru (Posner, 1954). Surface temperatures greater than 28 degrees C. and salinities as low as 32 per mille were observed. The invasion of warm water was accompanied by northerly winds, and a southward current was found as far south as Aguja Point (6° S.).

The large scale displacement of the Equatorial Countercurrent southward along the coast of Peru from December to April is commonly referred to as ''El Niño'' (Schott, 1951). Schott attributes the phenomenon to a shift of the meteorological equator southward across the equator and the consequent replacement of the southeast trade winds with northerly winds. These northerlies at the same time cause upwelling of cold and saline waters in the Gulf of Panama. To some extent this is an annual occurrence and only rarely is so pronounced as to affect conditions south of the Gulf of Guayaquil.

An interesting feature of the SCOFIELD observations is the center of warm water of low salinity located off the coast of Central America, south of Puntarenas, Costa Rica. This condition could be produced by warming *in situ* and by excess of precipitation over evaporation (Jacobs, 1951) during a period of several months or more of relative stagnation. Flow of these waters southward is suggested by the increase of temperature (2 degrees C.) and the decrease of salinity (one per mille) during a period of less than three weeks in the region north of the Galápagos Islands. Apparently displacement of the Equatorial

Countercurrent was accompanied by a wind-induced drift of surface water from the north, and the water found south of the equator between the Galápagos Islands and Ecuador was Equatorial Countercurrent water either modified by mixing with warm water of low salinity from the north, or overlain by such water. Schott (1931) in a study of the disastrous ''El Niño'' of 1891, compared meteorological conditions during the event with those of other seasons and other years. A clearer understanding of the origin and nature of the 1953 ''El Niño'' would result from a study of the more extensive historical weather records now available from this area, comparing 1953 records with those of other years.

SUMMARY

Oceanographic results of an experimental fishing expedition to the eastern tropical Pacific early in 1953 are discussed. Along a line at approximately 95 degrees W., both biological and other oceanographic observations resembled those previously described in the central equatorial Pacific. Between the Galápagos Islands and Ecuador the presence of unusual surface conditions (high temperature and low salinity) is related to the occurrence of ''El Niño'' observed along the coast of Peru.

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Journal of Paleontology
Vol. 29, No. 2, March, 1955
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CHANGES IN THE INVERTEBRATE FAUNA, APPARENTLY ATTRIBUTABLE TO SALINITY CHANGES, IN THE BAYS OF CENTRAL TEXAS[1]

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ABSTRACT—Previous studies on the invertebrate fauna of the bays of central Texas have been undertaken during periods of very low or highly variable salinity conditions. From 1948 to 1953 an extended drought with accompanying low river runoff caused salinities in these bays to increase to record highs, with little variation between maximum and minimum salinities during any particular month. Coincident with this extended high salinity period, the biotic communities within the bays changed considerably. Not only was there an invasion of many marine or open-Gulf species of invertebrates, but also a change was observed in the growth and appearance of the oyster reefs, one of the principal biotic assemblages. Another probable result of increased salinities was the disappearance of low-salinity mollusks which previous workers had found to be extremely abundant during the periods of low salinity.

This extended series of hydrographic observations should be useful to the paleoecologist in interpreting environmental changes in megafossil assemblages. Observations of this nature should prove useful in interpreting sedimentary facies, since many of the species involved occur as fossils at least as far back as the Pliocene. If the normal euryhaline fossil assemblages suddenly produce large numbers of high-salinity organisms such as sea urchins, corals and open-Gulf mollusks, one could assume that there had been drought conditions, with extended high salinities. These conditions can also be recognized by abrupt changes in shell structure of the common oyster, *Crassostrea virginica* (Gmelin), as well as the absence of the known low-salinity mollusks.

INTRODUCTION

A NUMBER of major papers have been published on the biological and hydrographic aspects of the shallow bays of the central Texas coast. Few of these studies have coincided with the recent drought conditions, and little information is available on the effects of droughts upon these bays and their fauna. As a result of the published work on this region (Galtsoff, 1931; Gunter, 1945, 1950a; Collier and Hedgpeth, 1950; Ladd, 1951; Puffer and Emerson, 1953; and Hedgpeth, 1953), the relationships of the faunal composition of the bays to the salinity regime have been established in general terms. In 1950–53 the author made an ecological study of the bays in the Rockport area (Fig. 1); this was begun as part of the regular oyster survey for the Texas Game and Fish Commission

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[1] Contribution from Scripps Institution of Oceanography, new ser., No. 754. This investigation was supported by a grant from the American Petroleum Institute, Project 51.

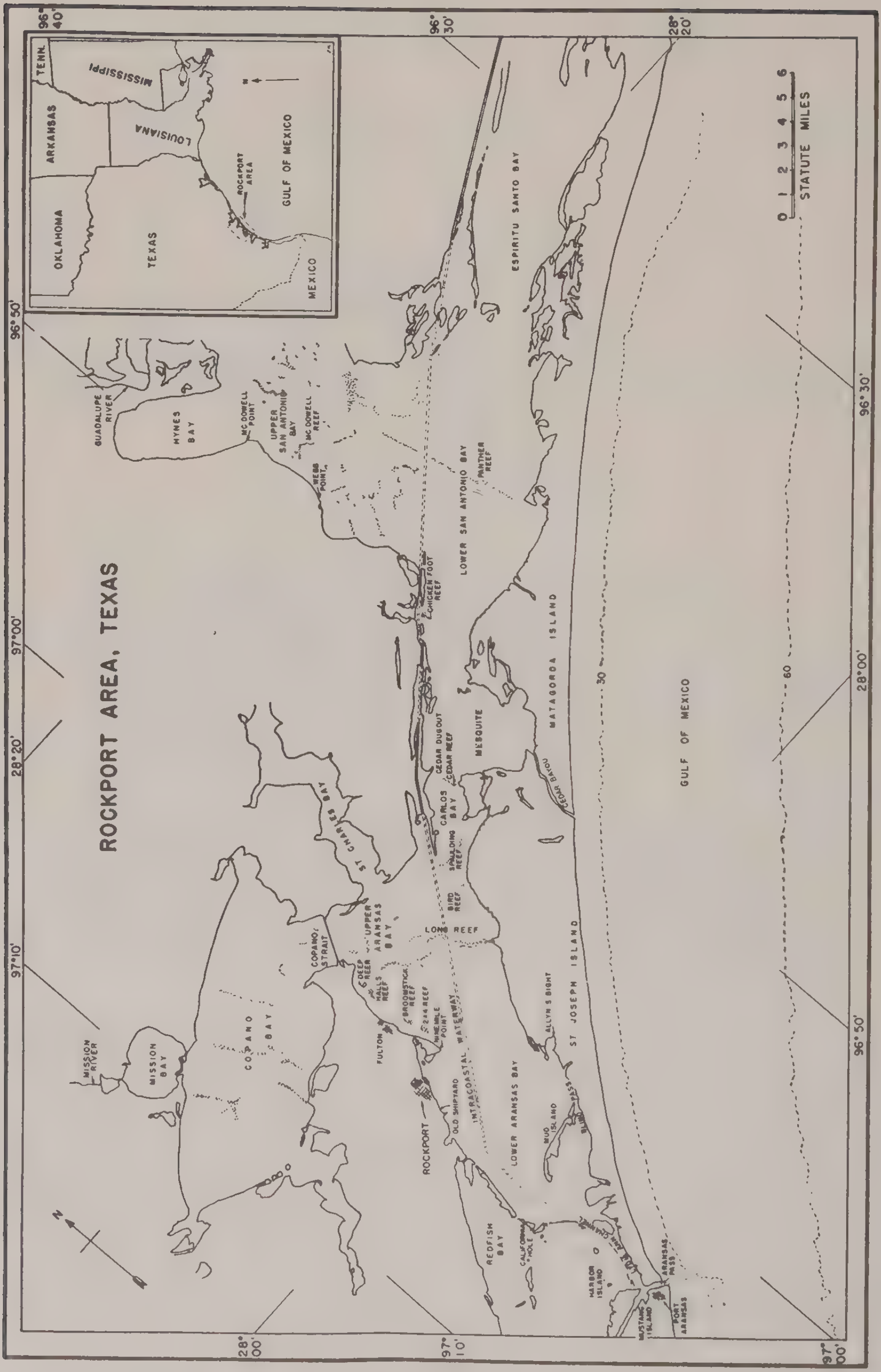
ROCKPORT AREA, TEXAS
TENN.
MISSISSIPPI
ARKANSAS
LOUISIANA
OKLAHOMA
TEXAS
ROCKPORT AREA
GULF OF MEXICO
MEXICO
N
GUADALUPE RIVER
HYNES BAY
MC DOWELL POINT
UPPER SAN ANTONIO BAY
MC DOWELL REEF
WEBB POINT
PANTHER REEF
LOWER SAN ANTONIO BAY
ESPIRITU SANTO BAY
CHICKEN FOOT REEF
MATAGORDA ISLAND
CEDAR DUGOUT
CEDAR REEF
MESQUITE
CARLOS BAY
CEDAR BAYOU
SPALDING REEF
BIRD REEF
LONG REEF
ST CHARLES BAY
COPANO STRAIT
UPPER ARANSAS BAY
DEEP REEF
HALLS REEF
BROOMSTICK REEF
2×4 REEF
NINE MILE POINT
INTRACOASTAL WATERWAY
FULTON
ROCKPORT
OLD SHIPYARD
LOWER ARANSAS BAY
MUD ISLAND
BLIND PASS
ALLYN'S BIGHT
ST JOSEPH ISLAND
MISSION RIVER
MISSION BAY
COPANO BAY
REDFISH BAY
CALIFORNIA HOLE
HARBOR ISLAND
ARANSAS PASS
MUSTANG ISLAND
PORT ARANSAS
GULF OF MEXICO
30
60
0 1 2 3 4 5 6
STATUTE MILES
96° 40'
96° 30'
28° 20'
96° 50'
97° 00'
28° 20'
97° 10'
28° 00'
97° 10'
97° 00'
96° 50'
28° 00'
96° 30'

FIG. 1—Location map.

and continued as part of the field work of Project 51, American Petroleum Institute. It was observed that the distribution of certain marine invertebrates, especially mollusks and echinoderms, differed from that indicated by previous major studies, which were undertaken during times of comparatively heavy rainfall. During the author's observations, salinities in the bays were much higher than during years of higher rainfall and greater stream discharge.

Salinity data for the years 1948–52 were determined by titration by the staff of the Marine Laboratory of the Texas Game and Fish Commission and by the staff of the Department of Oceanography, Texas A. & M. College for the American Petroleum Institute Project 51. For the period from March, 1952, to September, 1953, hydrometer readings from the U. S. Coast and Geodetic Survey tide station at Rockport, Texas, were used. The manner in which salinity values were obtained in the published data is given in the references cited in the captions for the various graphs.

River discharge data for the years 1936 to 1951 were obtained from the Surface Water Supply Papers of the U. S. Geological Survey. For the period from 1951 to September, 1953, data were supplied by Mr. S. D. Breeding of the Austin, Texas, office of the Surface Water Branch of the U. S. Geological Survey. Rainfall data for Victoria, Texas, were obtained from the *Local Climatological Summary of Victoria*, published by the U. S. Weather Bureau.

Faunal collections in the area were obtained by the use of shell and oyster dredges, oyster tongs, otter and beam trawls, Navy Electronics Laboratory snapper-type grab, and orange-peel grab, and by beach collecting. Over 500 stations were occupied as part of this study, and several stations in Aransas Bay were occupied weekly. The echinoderms and corals were identified by Dr. J. Wyatt Durham and Mr. Elton Puffer of the Museum of Paleontology, University of California, Berkeley, and the majority of the mollusks by Dr. Thomas E. Pulley, University of Houston, Texas, and Messrs. William K. Emerson and Elton Puffer of the Museum of Paleontology, University of California, Berkeley.

This work was made possible by the generous assistance of the staff of the Marine Laboratory, Rockport, Texas, and the staff of the American Petroleum Institute Project 51 at Scripps Institution of Oceanography at La Jolla, California. For invaluable assistance and coöperation, the author is particularly grateful to Drs. Joel W. Hedgpeth, Francis P. Shepard, Carl L. Hubbs, and Robert S. Arthur of Scripps Institution; Dr. Gordon Gunter and Mr. Martin W. Burkenroad of the Institute of Marine Science, University of Texas; Messrs. F. M. Dougherty and Byron B. Baker of the U. S. Navy Hydrographic Office, Suitland, Maryland; Messrs. E. D. McRae and Dewey W. Miles, formerly of the Rockport Marine Laboratory; and Messrs. Ernest Simmons, Robert Hofstettor and Howard Lee of the present staff of the Marine Laboratory. Sincere appreciation is extended to Mr. Cecil Reid, Chief Marine Biologist of the Texas Game and Fish Commission, and to Mr. J. L. Baughman, formerly of the Marine Laboratory, now of the Copano Research Foundation, for the use of their facilities and for data on file at the Marine Laboratory. The author also extends grateful appreciation to Mr. James Moriarty and Miss Majorie Browne of Scripps Institution for the preparation of the charts and graphs.

I. SALINITY, RIVER DISCHARGE AND RAINFALL RECORDS

A. Aransas Bay.—According to Collier and Hedgpeth (1950), the mean annual salinity of Aransas Bay for a "normal year" is approximately 19 to 20°/₀₀. This is further emphasized in a mimeographed report by Williams and Whitehouse (1952), which summarizes the previously published data and discusses the chlorinity data of the 1951–52 field seasons of A.P.I. Project 51. Although most of the data published before 1947 have been reviewed by Williams and Whitehouse (1952) and Whitehouse and Williams (1953), these summaries do not include salinity determinations made during the critical years of 1948, 1949, 1950, early 1951, 1952, and 1953. Hedgpeth (1953), however, cites salinity averages by months from 1948 through 1951, which were obtained from the United States Coast and Geodetic Survey tide station at the Marine

Laboratory of Rockport, Texas. Four months' data are missing from these years, and the accuracy of readings at the tide station is somewhat in doubt. After September, 1947, the mean monthly salinities remained above 20°/₀₀, and they remained above 30°/₀₀ from June, 1950, until September, 1952, attaining the very high value of 42°/₀₀ in August, 1951 (Fig. 2). A record 14-inch rainfall in the Rockport area in September, 1951, had no great effect on the average salinities in Aransas Bay. Somewhat increased rainfall in the Aransas Bay area and in the San Antonio-Guadalupe River drainage basin in late 1952 and early 1953, however, caused a considerable drop in salinity.

There has been a partial elimination of the gradients in salinity facies in Aransas Bay as determined by Ladd (1951). The differences in salinity between Lydia Ann Channel and lower Aransas Bay and those of upper Aransas Bay near Carlos Bay and in the Copano Strait were 5.6°/₀₀ in November, 1951, and 2.2°/₀₀ in January, 1952. During Ladd's investigation, the difference in salinity between opposite ends of Aransas Bay was approximately 12°/₀₀.

Salinities in Aransas Bay have consistently risen above 20°/₀₀ during the summer

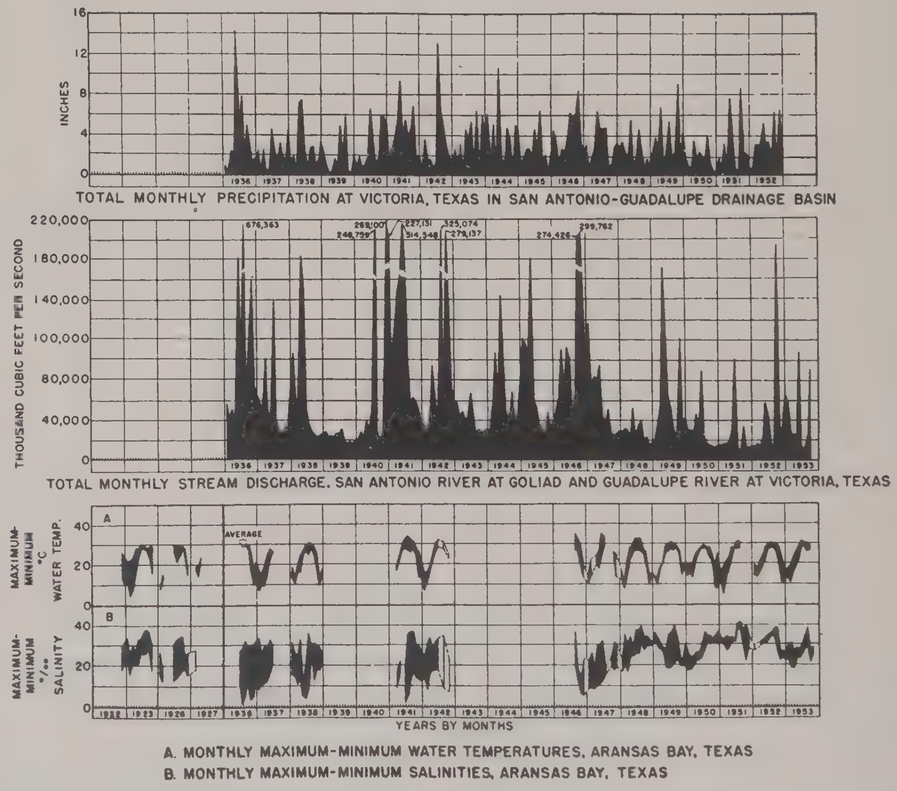

FIG. *2*—Comparison of water temperatures and salinities of Aransas Bay, Texas, with rainfall and river discharge in the San Antonio-Guadalupe river system. Salinities and water temperature data from 1922–23 (Collier and Hedgpeth, 1950), from 1926–27 (Galtsoff, 1931), and from 1936–46 (Collier and Hedgpeth, 1950).

months in the past, but the change in salinity can best be demonstrated in the ranges between maximum and minimum values during each month. Between 1926 and 1947, the salinity has ranged from 10 to 30°/oo during most of the months, even in the summer. After 1947 the difference between maximum and minimum became very small at all seasons (Fig. 2), although there were very few readings for some months. During the months of moderately high rainfall in the years 1936, 1941, 1942, 1946, and 1947, salinity conditions in Aransas Bay were highly variable throughout the year and appear to be somewhat more concentrated in the low range of salinities from 5 to 25°/oo (Fig. 2). However, during years of drought, in 1948 to 1952, in the Rockport Bays, salinities were far less variable and were more concentrated in the upper range (25 to 40°/oo).

B. San Antonio Bay.—San Antonio Bay has also shown a gradual increase in salinity since 1950, in spite of heavy discharges from the Guadalupe River in June, September and October, 1951 (Fig. 2). Galtsoff (1931) states that in 1926 salinity values for upper San Antonio Bay were in the neighborhood of 4 to 10°/oo and for lower San Antonio Bay from 10 to 17°/oo. Baker (1950) found salinity ranges from 13.1 to 24.4°/oo in lower San Antonio Bay in 1950. In 1951, the author found salinity values ranging from 20.3 to 32.1°/oo in lower San Antonio Bay and Mesquite Bay, whereas the A.P.I. field party from Scripps Institution obtained salinity values of from 23.90 in upper San Antonio Bay to 41.42°/oo in lower San Antonio Bay in July and August, 1951. These are the highest salinities to be recorded from this usually low salinity bay. Williams and Whitehouse (*op. cit.*) state that salinities in lower San Antonio Bay still ranged from 27.39 to 31.16°/oo (converted from chlorinities) in January and February, 1952, although upper San Antonio Bay salinity values were much lower. Salinities in late 1953 were still well above the "normal" of 10 to 17°/oo as suggested for San Antonio Bay by Ladd (1951).

C. Copano Bay.—In the spring and summer of 1951, salinities were generally higher in Copano Bay than in Aransas Bay. At no time during the period from July, 1950, to August, 1951, was a salinity lower than 32.2°/oo observed in Copano Bay. The highest observed salinity was 40°/oo, and the mean for that period was about 36°/oo (Fig. 3). The maximum-minimum range is much narrower and the rise more spectacular for Copano Bay than in Aransas Bay, as can be observed by comparing figures 2 and 3. Higher salinities are to be expected in shallower Copano Bay in relation to periods of reduced rainfall and high evaporation over the Copano watershed, as pointed out by Collier and Hedgpeth (1950). River runoff from Mission River is so slight during dry years (as compared to the San Antonio-Guadalupe rivers), that practically no freshening of this bay can occur. Evaporation, then, can have a very telling effect upon this shallow enclosed bay.

D. Redfish Bay.—Redfish Bay, on the west side of Aransas Bay and behind Harbor Island, is nearly landlocked, extremely shallow, and close to the higher salinity waters of Aransas Pass; therefore, it is usually subject to rather high salinities in the summer. In the absence of salinity data for earlier years. Little can be said concerning the changes in the bay except for the period since 1947. According to salinity values obtained by Hedgpeth (unpublished data), Baker (1950), and the author, salinities in Redfish Bay ranged from 39.8°/oo at the peak of the dry season in 1950 to 21.7°/oo in the winter months of 1949 and 1950. From October, 1947, to May, 1948, February to April, 1949, and October, 1949, to June, 1950, salinities remained below 30°/oo. After June, 1950, salinities rose above 30 and remained above 31°/oo throughout 1950 and 1951.

E. Mesquite Bay.—The maximum and minimum salinities for Mesquite Bay are shown on figure 4. Although data are scarce during so-called wet years, it can be seen that in 1926, 1927, 1936, and 1937 salinities ranged between 4 and 19°/oo, and from 1947 to 1950 from 14 to 28°/oo. During these years salinities were still essentially those of a low- to medium-salinity bay. However, in 1950 and 1951 salinities were not obtained below 22°/oo, and at one time they ranged to above 40°/oo. A record of salinity values obtained by Mr. Ernest Simmons of the Marine Laboratory, taken approximately every two hours in the center of Cedar Bayou (Table 1),

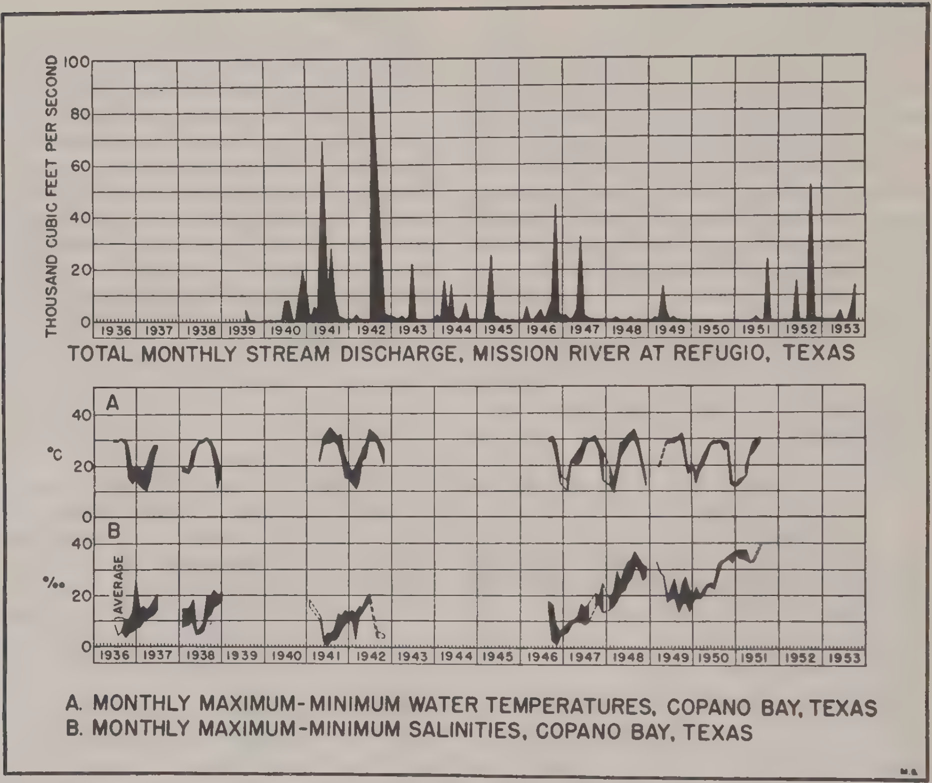

FIG. *3*—Comparison of salinities, water temperatures of Copano Bay, and Mission River stream discharge. Salinity and water temperature data for 1936 to 1947 obtained from Collier and Hedgpeth (1950).

shows very little change (not more than $1.6^{\circ}/_{oo}$) in salinity over a three day period. Since this period covered at least two complete astronomical tide cycles, it would appear that tides apparently do not bring enough Gulf water into Mesquite Bay to raise the salinity noticeably. From the above data it would appear that Mesquite Bay is more affected by river runoff and evaporation than by influx of Gulf water.

F. The Gulf of Mexico.—The salinities of the coastal fringe of the Gulf of Mexico in the vicinity of Port Aransas and Cedar Bayou have risen to a slight degree recently, according to the few data available (Fig. 4). Phleger (1951) notes that surface salinities taken off Corpus Christi, near Aransas Pass, by the *Atlantis* in 1935, ranged from about 31 to $33^{\circ}/_{oo}$. These low values were attributed to fresh water runoff and occurred simultaneously with the very low salinities in the bays. Gunter (1945) states that the mean salinity of this coastal water is about $32^{\circ}/_{oo}$. Salinity observations for the spring and summer of 1951 close to shore in the vicinity of Port Aransas indicated a range of from 36.19 to $39.90^{\circ}/_{oo}$, 4 to 6 parts higher than during the "wet" years of 1935 to 1941.

G. General Considerations of River Discharge, Rainfall and Salinity.—In order to determine whether droughts are responsible for the increased salinities in the Rockport area, all available discharge data for the rivers which empty into these bays, as well as representative rainfall data from the drainage areas, have been plotted with the associated salinites and water temperatures.

TABLE 1.—RECORD OF SALINITIES TAKEN AT CEDAR BAYOU FROM 11:45 APRIL 18, TO 07:00 APRIL 21, 1950; SUPPLIED BY MR. ERNEST SIMMONS, T. G. & F. C.

Date	Hour	Salinity °/oo
4/18/50	1145	22.7
	1350	22.6
	1558	22.7
	1745	22.9
	2000	22.9
4/19/50	0730	22.6
	0900	22.1
	1355	22.5
	1455	22.4
	1715	22.9
	2000	22.9
4/20/50	0730	22.9
	0945	22.8
	1154	22.4
	1350	22.4
	1600	22.3
	1755	22.2
	2020	22.3
	2200	22.9
2/21/50	0700	23.7

When there are extended periods of heavy runoff from the San Antonio-Guadalupe and Mission rivers, as during 1936, 1938, 1941, 1942, 1946, and early 1947, there is a corresponding drop in salinities in the bays into which they empty for the same years (Figs. 2 and 3). According to these graphs the effect of increased runoff is felt in the bays within less than a month, and likewise, as soon as the runoff is reduced, salinity values rise rather rapidly to the values occurring prior to the runoff. The total rainfall by months in the drainage areas of the San Antonio-Guadalupe rivers is also reflected in the total monthly discharge figures of these rivers (Fig. 2).

In order to demonstrate more clearly the long term changes in salinity in the Texas bays, a graph was prepared showing the total yearly river discharge for the San Antonio-Guadalupe rivers as compared with the yearly average salinities in Aransas Bay (Fig. 5). According to this graph those periods from 1934 to approximately 1948 show correspondingly high runoff and low salinity. Starting in 1947, river discharge became less and less (associated with decreased rainfall), and the average yearly salinities increased from 20 to 35°/oo. Prior to 1947, average yearly salinities ranged from 15 to 20°/oo. This graph has been expanded to in-

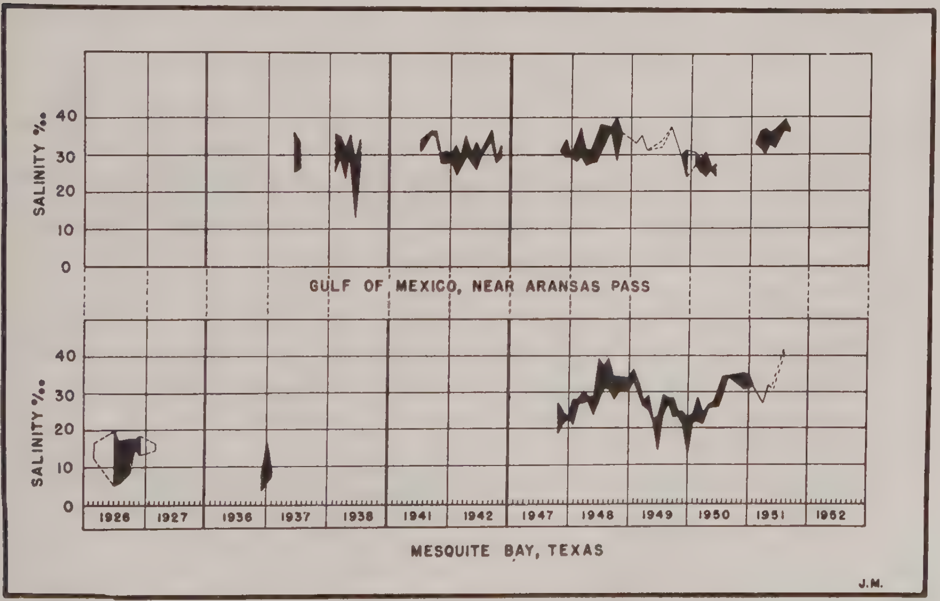

FIG. 4—Comparison of salinity data from Mesquite Bay and the Gulf of Mexico. Data for 1926–1927 from Galtsoff (1931), for 1936–1947 from Collier and Hedgpeth (1950).

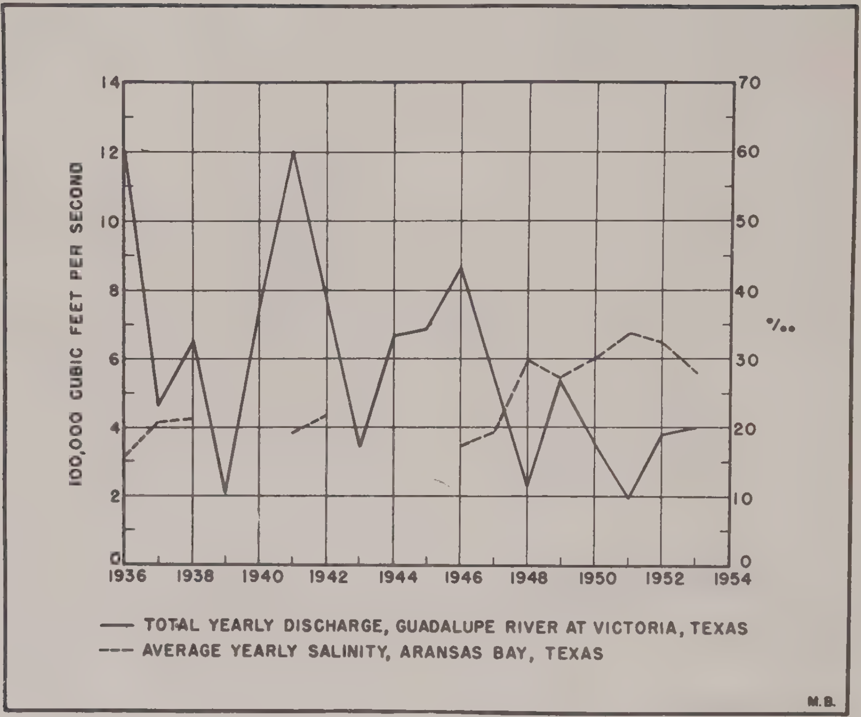

Fig. 5—Comparison of total yearly discharge of Guadalupe River with average yearly salinity of Aransas Bay, Texas.

clude monthly mean salinities and monthly mean river discharge (Fig. 6) for Aransas Bay in order to demonstrate the relationships between salinity and river discharge on a monthly basis. Again it may be observed that with monthly increases in river discharge, salinity decreases are reflected in Aransas Bay within a month. The rise in salinities from February, 1948, through 1953 is depicted somewhat more spectacularly in the plots of the mean salinities than in maximum and minimum salinity graphs, although the significant narrow range of salinity during the drought years is not apparent.

II. BIOLOGICAL CONDITIONS

A. The Change in Salinity in Relation to Oyster Reef Conditions.—Previous marine biological studies have been made in the central Texas coastal area during periods of much lower salinities than have been observed during 1948 to 1953. The composition of the biotic communities has changed considerably during this high salinity period. One organism which appeared to be considerably affected by the increased salinity was the oyster, *Crassostrea virginica* (Gmelin), which is the principal component of the extensive shell reefs in this area. The salinity increase was briefly noted by Puffer and Emerson (1953) and was cited as a possible explanation for reduced production of oysters in the Texas bays. This mollusk has been the most studied organism in the local bays, receiving considerable attention from Galtsoff (1931, 1942), Gunter (1950a), Baughman and Baker (1950), Puffer and Emerson (1953), and various investigators for the Texas Game and Fish Commission throughout the past 50 years. It is generally considered that this oyster is best adapted to an estuarine environment, with a salinity of 12 to 19°/oo (Ladd, 1951 and Gunter, 1953), and does not form extensive reefs in areas of high salinity. However, Korringa (1952) states that experimental evidence conflicts with field observations, and no definite conclusion can be drawn as to exact salinity preferences. Amemiya (1926) determined in the laboratory the lower and upper salinity limits of the developmental stages of the American oyster, *C. virginica*. Amemiya found that below $15^\circ/_{oo}$ and above $30^\circ/_{oo}$, abnormal segmentation of the oyster larvae took place, and very few shell-bearing larvae were formed. Such developmental abnormalities could very well limit populations in waters of either very low or very high salinity.

A change in the growth-rate and meat condition of the oyster was noted during the period of increased salinity (1950–1952). According to Byron B. Baker (personal communication) oysters from 1948 to the fall of 1950, were thin, flabby and tasteless, even when they were not spawning. Glycogen-content tests by the Texas A. & M. Research Foundation (unpublished communication in the files of the Texas Game and Fish Commission), showed a very low glycogen content for oysters in Aransas Bay during the period of 1948 to 1950. For several years, when the salinities were generally below $25^\circ/_{oo}$, no appreciable shell growth was observed in oysters larger than

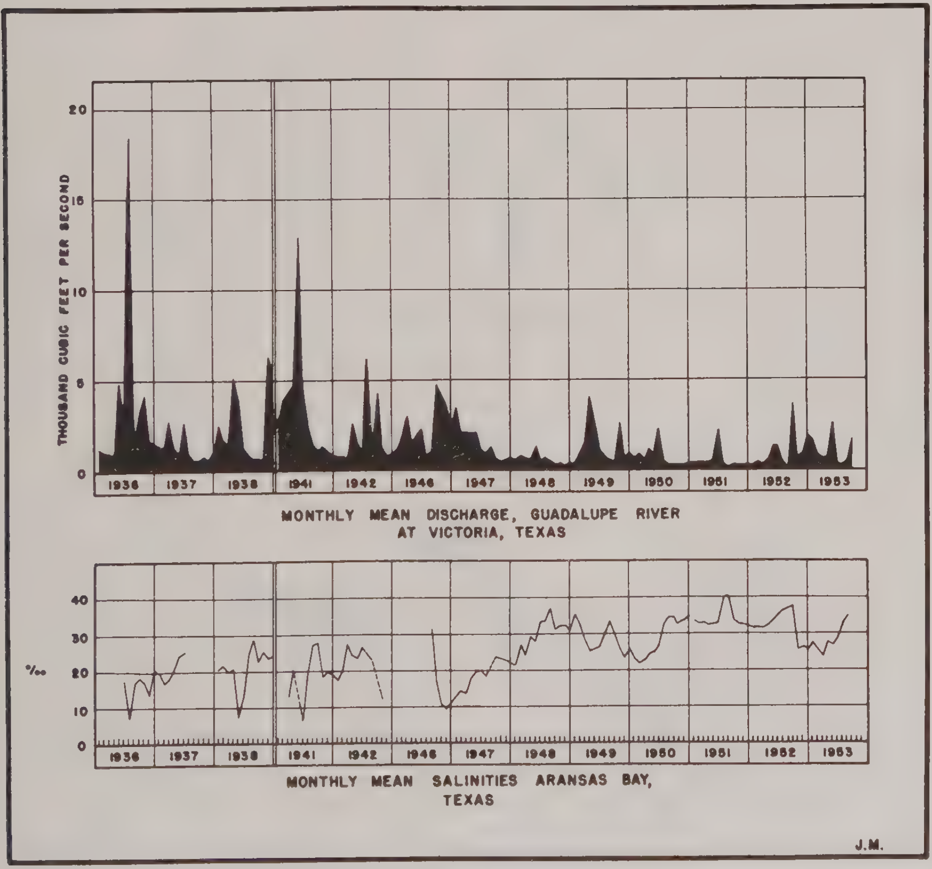

FIG. *6*—Comparison of monthly mean salinities of Aransas Bay, Texas, with monthly mean river discharge of Guadalupe River, Texas.

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two or three inches. After the salinities had risen above 30°/₀₀ a definite change was observed in most of the oysters. The rate of new shell growth increased in old oysters (those with very thick but stubby valves). In less than two months, many old oysters produced new extensions of the valves of two or three centimeters in length, and by March, 1951, most oysters observed had long, highly-colored, crenulated valves of new, sharp growth. Many oyster men and biologists native to this locality stated that such rapid and long growth had previously never been observed in so short a period. Oyster glycogen-content increased fairly rapidly, according to tests performed by the author. It is generally considered that oysters are at their best in Aransas Bay during the winter months, as intense spawning activity saps their vitality whenever water temperatures remain above 20°C for any length of time (Gunter, 1942). During the spring and summer of 1951, most of the oysters sampled were of exceptional fatness

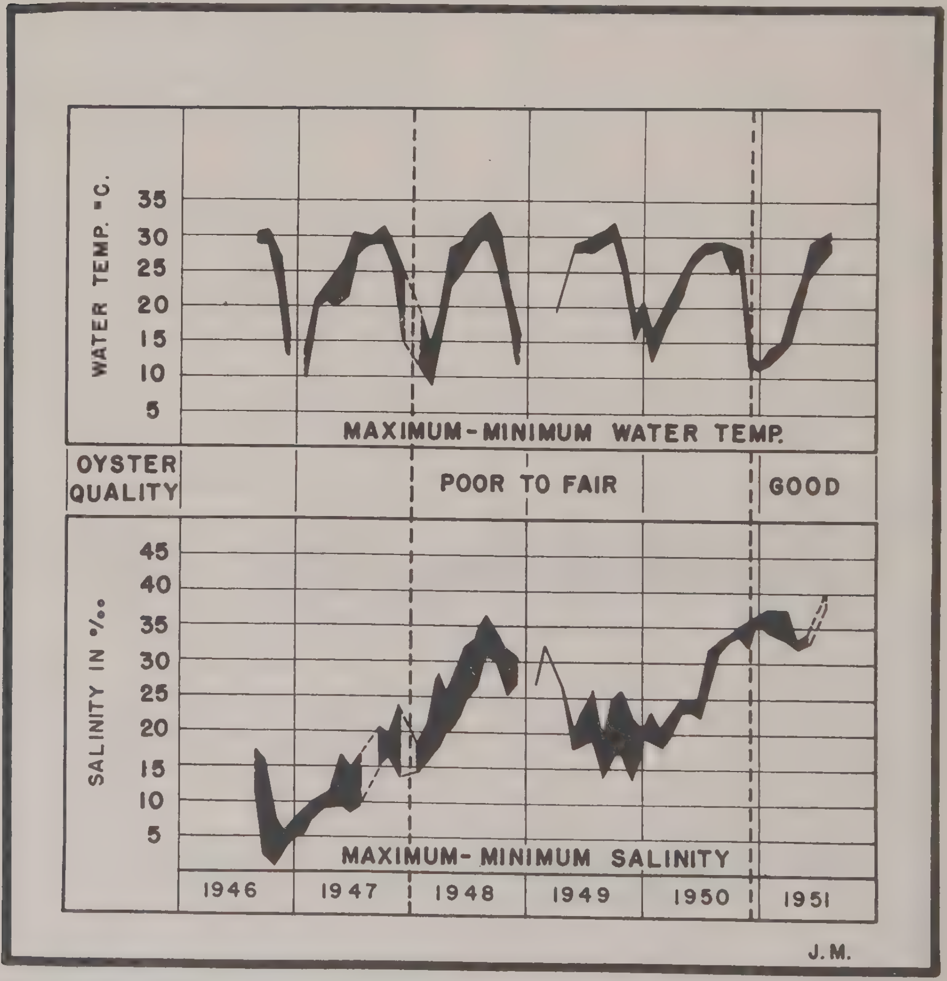


Fig. 7—Comparison oyster quality (determined by glycogen analysis and other oyster quality tests) with water temperature and salinities of Copano Bay, Texas.

and quality, even though in spawning condition (Fig. 7). A change in oyster appearance and quality was again observed during January through March, 1952. Instead of rapid new growth, as in the previous year, most oysters had little new growth, although they were of continued high quality. Oysters were reported to be dying in large numbers in Copano Bay during 1952 (R. Hoffstettor, personal communication), although in 1951 Copano Bay oysters were larger than previously observed for several years. It might be mentioned that with the declining salinities of the latter part of 1953, oyster production is apparently improving in Aransas Bay.

An indication of a change in the faunal composition of the oyster reefs in central Texas bays is the presence of large numbers of the small oyster, *Ostrea equestris* Born. This oyster is normally found in waters of high salinity, and seldom occurs abundantly in any of the bays, although it has always been present in Lydia Ann Channel and Aransas Pass (J. W. Hedgpeth, personal communication). Examination of oyster spat from Copano Bay in March, 1952, revealed that almost half of the small oysters of from an inch to an inch and a half in diameter were adults of *Ostrea equestris*. Samples of spat obtained from Long Reef, Tin Can Reef, and other small reefs in Aransas Bay were composed of over 50 per cent *O. equestris*. This oyster never grows very large; but it could supply a shell base for the common oyster to set when the bays return to lower salinity. Large numbers of *O. equestris* in old *C. virginica* reefs buried in Recent and possibly Pleistocene sediments probably indicate high salinity conditions at the time of deposition.

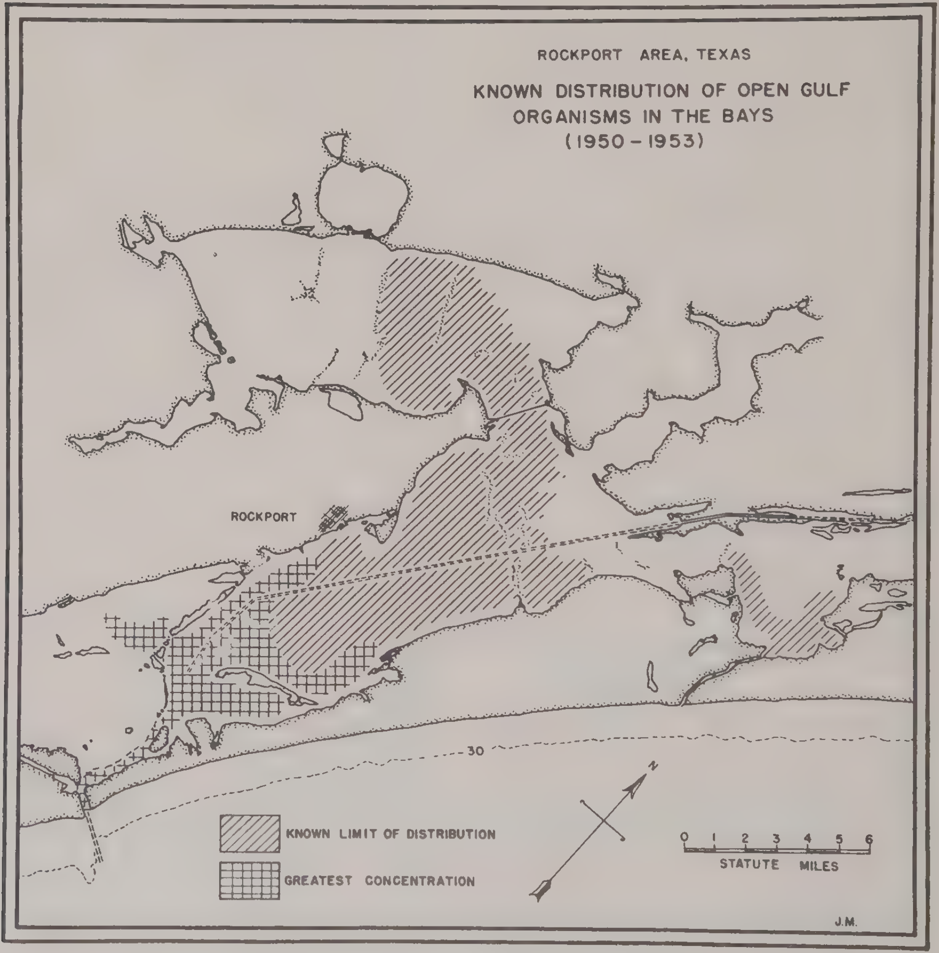
B. Apparent Faunal Changes in the Aransas Bay System.—During the period of extended high salinity, many organisms were collected in Aransas Bay which had never been reported from this area before, including some previously considered characteristic of the Gulf waters. The most unusual of the "marine invasions" into the bays was that by various echinoderms usually confined to waters of higher salinity, and rare or not hitherto reported in Aransas Bay proper. These include large numbers of starfish, abundant *Luidia clathrata* (Say) and rare *L. alternata* (Say). Other echinoderms collected year-round were many sand dollars, *Mellita quinquesperforata* (Leske), two species of sea urchins, *Arbacia punctulata* (Lamarck) and *Lytechinus variegatus* (Leske), and five species of ophiurans, *Ophiolepis elegans* Lütken, *Hemipholis elongata* Say, *Amphiodia limbata* (Grube), *Ophioderma* sp., and *Ophiothrix* sp. Hedgpeth (Whitten, Rosene and Hedgpeth, 1950) reports two brittle stars, *Hemipholis elongata* and *Ophiactis* sp., one sand starfish, *Astropecten antillensis* Lütken, and the sea urchins, *Arbacia punctulata* and *Lytechinus variegatus*, from the vicinity of Port Aransas and Aransas Pass in the open Gulf. In the present collections, except for the brittle stars which have been found over most of the sand-slit-clay bottoms of Aransas Bay, parts of Copano, Mesquite and lower San Antonio Bays, most of the echinoderms have been collected from the northeast end of Lydia Ann Channel, near Mud Island, and in the southeastern section of Aransas Bay. Although the Mud Island area has always presented a somewhat different faunal appearance from the rest of Aransas Bay, the echinoderms mentioned above have not been noted in previous publications (which, however, did not attempt to catalogue the fauna of Aransas Bay) or at least have not been observed as year-round residents.

Large numbers of the sea pansy or sea liver, *Renilla mülleri* Kölliker, and an increasing number of colonies of whip coral, *Leptogorgia setacea* (Pallas), have also been taken during all seasons around Mud Island, and in the Intracoastal Waterway, well up into Aransas Bay as far as Rockport. It was observed that strands of whip coral in the center of Aransas Bay were smaller than those living closer to Gulf waters. Those obtained directly off Rockport were from two to three inches tall, whereas those found near Mud Island and in nearshore Gulf waters were two to three feet long. The author also found living star coral, *Astrangia astreiformis* Milne Edwards and Haime, in Aransas Bay as far northeast as the old shipyard at Rockport. Many lumps of dead coral have also been found in Lydia Ann Channel and around Mud Island. Ladd (1951) lists this coral as abundant in lower Aransas Bay, near the passes into Redfish

Bay and Lydia Ann Channel, and his observations have been confirmed by Hedgpeth (personal communication). A map, figure 8, shows the farthest advance of the open Gulf organisms. Neither Gunter, Hedgpeth, Reed (1941), nor Ladd lists *Renilla* or *Leptogorgia* as inhabitants of Aransas Bay, or even Lydia Ann Channel which is usually more saline than the bays. Hedgpeth (personal communication) suggests that *Renilla* may have always been present in small numbers in Lydia Ann Channel.

A wide occurrence of tectibranchs, which Hedgpeth (Whitten, Rosene, and Hedgpeth, 1950) lists as probably *Tethys floridensis* Pilsbry, was also noted in the spring of 1951. In 1951, hundreds of these large (4 to 10 inches long) animals were observed in all parts of Aransas Bay and Corpus Christi Bay. Whether this influx of sea hares can be associated with the increase in salinity, or is part of a resurgent population, is a matter for speculation. Hedgpeth (1950) and Reed (1941) state that they are usually found on beaches after storms, but are occasionally taken in the bays.

The distribution of two arthropods, *Penaeus setiferus* (Linné) and *Callinectes*



ROCKPORT AREA, TEXAS
KNOWN DISTRIBUTION OF OPEN GULF ORGANISMS IN THE BAYS (1950 – 1953)
ROCKPORT
30
N
KNOWN LIMIT OF DISTRIBUTION
GREATEST CONCENTRATION
0 1 2 3 4 5 6
STATUTE MILES
J.M.

Fig. 8

danae Smith, also appears to have changed during this high-salinity period, and it may or may not have been associated with the salinity change. Of the two, *P. setiferus*, the common commerical or white shrimp, has shown the greater change. Prior to 1949, when the salinity was low, this shrimp formed the major portion of the commerical net hauls of shrimp in the Texas bays in the fall. According to Hildebrand and Gunter (1953), however, production of white shrimp in Texas fell from 2 to 7 million pounds from 1949 to 1951. An analysis of otter-trawl catches taken by the author during the fall of 1951 and spring of 1952 showed that only one to five per cent of the total shrimp consisted of *P. setiferus*, while juveniles of *P. aztecus* Ives and *P. duorarum* Burkenroad comprised the bulk of the shrimp catch. Gunter (1950) discussed the seasonal abundance of all three species of shrimp in detail, and emphasized that *P. setiferus* occurs in vast abundance and supports the commerical catch in the fall. Burkenroad (1951) states that in the Aransas Bay area the sharp decline in the numbers of young white shrimp is probably associated with the recent high salinities. Hildebrand and Gunter (1953) indicate that there is a high correlation between the production of white shrimp and the increase or decrease of rainfall. Since, as indicated in the discussion of the physical-chemical factors, there is a rather high degree of association between rainfall, runoff and salinity in the Texas bays, it is reasonable to assume that salinity has been at least partly responsible for the decrease in shrimp. Hildebrand and Gunter state that the correlation may be either with salinity *per se* or with some unknown factor governed by salinity.

The abundance of *Callinectes danae*, which in the summer of 1951 and spring of 1952 was far more numerous than in the previous year, may also be asssociated with high salinity. This crab is commonly known as the Gulf crab, and is smaller than the common edible blue crab, *Callenictes sapidus* Rathbun. Gunter (1950) compares catches of the Gulf crab from Aransas Bay and the Gulf of Mexico in 1941 and 1942, and shows very few individuals present in Aransas Bay, as compared to the large numbers in the open Gulf at the same time. Daugherty (1952), however, made collections of *C. danae* during the early portions of this period of increased salinity and observed that far greater numbers of this crab were present in the bays than previously, and that they were present there throughout the year. Personal observations during 1950, 1951, and 1952 also showed an increase in numbers of the Gulf Crabs in the bays, although actual counts were not made from month to month. Hauls taken in March, 1952, contained many more Gulf crabs than blue crabs, and at times the Gulf crabs constituted a major portion of the total trawl catch.

Considered somewhat unusual for these Texas bays was the occurrence of 23 species of living mollusks which usually occur in waters of high or oceanic salinity and have never been reported living in these bays before. Because of the large number of species of mollusks involved, and the fact that many other investigators have dealt with their distribution here in the past, a table has been prepared comparing the distribution of the mollusks during the times of high salinity and during the times of low salinity (Table 2). The majority of collections of mollusks from the Texas bays have been made during times of reduced salinity; therefore, the species of mollusks said to be indicative of the bays are quite different from those which are now abundant, although most of the species found previously are still present. However, *Rangia cuneata* (Gray), a low salinity mollusk, has virtually disappeared. At the time his collections were made in upper San Antonio Bay (1940), when the salinities ranged from 4 to 9°/₀₀, Ladd collected large numbers of *Rangia*, of which most were living. Burkenroad (personal communication) also states that he has found large populations of *Rangia* living in this locality during times of very reduced salinity. During the summer of 1951 and spring of 1952, when salinities were generally much higher (11 to 20°/₀₀), no living specimens of *Rangia* were taken in San Antonio Bay although extensive collections were made throughout all of the bay. Associated with *Rangia* is the minute gastropod, *Littoridina sphinctostoma* Abbott and Ladd, which Ladd found alive only in waters of very low salinity. In 1940 it was said to be

TABLE 2.—DISTRIBUTION OF MARINE MOLLUSKS IN RELATION TO SALINITY IN CENTRAL TEXAS BAYS, 1893–1953

A—Alive. D—Dead. X—Reported, condition not stated. L—Alive, not reported before.

Species	Collector																			
	Singley, to 1892[1]		Mitchell, 1894[2]		Cross & Parks, 1935[3]		Reed, 1936–41[4]		Ladd, 1940[5]		Gunter, 1941–42[6]*		Hedgpeth, 1946–48[7]*		Pulley, 1947–50[8]		Emerson & Puffer 1951–52[9]		Parker & Lee 1951–53[10]	
	Bay Salinity Range																			
	Unknown		Unknown		2–25°/oo		2–25°/oo		5–35°/oo		5–35°/oo		7–39°/oo		9–40°/oo		20–42°/oo		20–42°/oo	
	Occurrence																			
	Gulf	Bay	Gulf	Bay	Gulf	Bay	Gulf	Bay	Gulf	Bay	Gulf	Bay	Gulf	Bay	Gulf	Bay	Gulf	Bay	Gulf	Bay
GASTROPODA																				
Diodora cayenensis	D								D						X	X				
Neritina virginea		A				X				A						X				A
Littorina irrorata				A		A		X					A	A		X	D	D		A
Littorina nebulosa													A		X				A	
Littorina ziczac										A			A		X	X				
Littoridina sphinctostoma										A							D	D		D
Architectonica nobilis			D		X										X		D		D	
Vermicularia fargoi		D		A	X				D	D					X			A		A
Caecum pulchellum									D	D					X		D	D		D
Modulus modulus	D			D					D	D					X			D	D	D
Bittium varium		D						X	D	D						X	D	D		D
Cerithidea pliculosa		D		A			X		D	A						X	D	D		D
Cerithium variabile		D		D		X	X		D	A					X		D	D		D
Seila adamai	D														X					
Epitonium angulatum	D					X	X			D					X			D		L
Epitonium rupicolum							X								X			D		L
Janthina janthina			D	D			X								X				D	
Janthina globosa						X									X				D	
Niso interrupta	D														X					
Odostomia impressa		D							D	A						X		A		A
Crepidula fornicata	D			D	X								A		X		D	D	D	L
Crepidula glauca					X	X	X		D	A						X				
Crepidula plana				A					A	D					X		D	A	A	A
Strombus alatus	D		A		X		X								X				D	L
Natica pusilla			A		X				A	D					X	X	D	L	A	L
Polinices duplicata	D		A		X		X		A	D			A		X		D	L	A	L
Sinum perspectivum	D				X										X			L	A	L
Simnia uniplicata															X		D	L	A	L
Phalium granulatum	D		D		X		X						A		X		D		A	
Distorsio clathrata			D		X										X		D		D	
Tonna galea			A		X		X				A				X				D	
Murex fulvescens	D		D		X		X								X				D	
Murex pomum					X	X	X										D		D	D
Thais haemostoma haysae-floridana				A	X	X		X	A		A		A	A		X	D	D	A	A
Anachis avara semiplicata		D							A	A			A	A	X			A	A	A
Anachis obesa	D								A	A						X		A	A	A
Mitrella lunata	D									A						X		A		A
Nassarius vibex	D			A					D	A						X	D	D	D	D
Nassarius acutus	D					X			A	A			A		X		D	D	A	A
Fasciolaria distans	D		D		X		X						A		X		D	D	D	D
Fasciolaria gigantea			D		X										X				D	
Fasciolaria tulipa			D		X										X				D	
Cantharus cancellaria					X	X			A	A					X	X	A	D	A	A
Cantharus tinctus													A						A	
Busycon spiratum	D		A		X		X		A	D	A				X		D		D	
Busycon perversum		D	A		X	X	X		D		A				X	X	D	L	A	L
Oliva sayana	D		A		X				A						X		D	D	A	L
Olivella mutica	D				X				A	D					X				A	
Cancellaria reticulata															X					L

Marginella apicina		D													X					
Mangelia cerinella	D															X		L		
Terebra cinerea							X								X		D		A	
Terebra dislocata	D						X								X		D		D	
Terebra protexta		D								D								D		
Actaeon punctostriatus															X			D		
Acteocina canaliculata	D									A						X		D		A
Bulla occidentalis		D		D		X							A			X	D			L
Haminoea elegans				A												X				D
Melampus coffeus				A		X										X		D		D
Siphonaria pectinata													A	A						A
SCAPHOPODA																				
Dentalium texasianum		D							D	A					X	X		D	D	A
PELECYPODA																				
Nuculana acuta		D								A					X			A	D	A
Nuculana eborea										A					X	X				A
Anadara ovalis		D	D	A	X				A	A					X		D	A	D	A
Anadara chemnitzi															X		D			
Anadara braziliana		A			X		X		D						X		D		D	
Anadara secticostata					X														D	
Aandara transversa		D	D		X				A	A					X		D	A	D	A
Arca umbonata			D												X		D		D	
Noetia ponderosa	D				X		X		A	D					X		D	D	A	D
Brachidontes recurvus		A		A	X			X		A			A	A		X				
Brachidontes exustus		A		D												X		A		A
Lithophaga bisulcata													A							
Volsella demissa granosissima		D		A																
Modiolus tulipus						X	X			A					X		D		D	
Atrina rigida		D		A		X	X			A						X		D	D	A
Atrina serrata			D	D	X		X								X		D		D	
Aequipecten gibbus amplicostatus		A			X	X	X		D	A						X	D	A	D	A
Aequipecten gibbus concentricus	D				X	X											D	D	D	
Anomia simplex		D		A		X			D	A			A	A		X	D	A	D	A
Ostrea equestris											A		A	A	X		D	A	D	A
Crassostrea virginica		A		A	X	X		X	D	A		A	A	A		X	D	A	D	A
Crassinella martinicensis		A							D	A								D	D	A
Cardita floridana		D	D	D					D	D					X	X	D	D	D	D
Polymesoda caroliniana				A												X	D		D	
Polymesoda floridana		A		D						D						X		D		
Diplodonta punctata															X			L		
Diplodonta semiaspera																		D		
Anodontia schrammi															X		D	D	D	D
Anodontia alba				D											X		D	D	D	L
Lucina amiantus									D						X				A	L
Lucina crenella		D			X				D	D					X			D		D
Lucina floridana									D						X		D		D	
Lucina pectinata	D			A						A					X	X	D	D	D	
Dinocardium robustum	D		A		X		X		D	D					X		D	D	D	D
Laevicardium laevigatum	D		D												X		D	D	D	D
Laevicardium mortoni				A	X					A					X	X		A		A
Trachycardium muricatum	D			A	X		X		A	A					X	X	D	A	D	A
Anomalocardia cuneimeris									D	A						X	D	A	D	A
Chione cancellata		D	D			X			A	A					X	X	D	A	D	A
Chione intapurpurea															X				D	D

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* Collection only made on living forms.

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[9] Data compiled by Elton Puffer and William K. Emerson for the American Petroleum Inst., Project 51, during Jul.–Aug. 1951 and Feb., 1952.

[10] Data compiled by Robert H. Parker and Howard K. Lee for the Texas Game and Fish Commission and A.P.I. Project 51 during the years 1950 through 1953.

(*Continued on next page*)

TABLE 2.—*Continued*

A—Alive. D—Dead. X—Reported, condition not stated. L—Alive, not reported before.

Species	Collector																			
	Singley, to 1892[1]		Mitchell, 1894[2]		Cross & Parks, 1935[3]		Reed, 1936–41[4]		Ladd, 1940[5]		Gunter, 1941–42[6]*		Hedgpeth, 1946–48[7]*		Pulley, 1947–50[8]		Emerson & Puffer 1951–52[9]		Parker & Lee 1951–53[10]	
	Bay Salinity Range																			
	Unknown		Unknown		2–25°/₀₀		2–25°/₀₀		5–35°/₀₀		5–35°/₀₀		7–39°/₀₀		9–40°/₀₀		20–42°/₀₀		20–42°/₀₀	
	Occurrence																			
	Gulf	Bay	Gulf	Bay	Gulf	Bay	Gulf	Bay	Gulf	Bay	Gulf	Bay	Gulf	Bay	Gulf	Bay	Gulf	Bay	Gulf	Bay
Chione clenchi															X				A	
Cyclinella tenuis			D						D	D					X	X				
Dosinia discus	D		D		X				A	D					X	X	D	D	A	L
Macrocallista nimbosa			D												X				D	D
Pitar texasiana															X	X	D	D	D	
Pitar cordata															X				A	
Mercenaria campechiensis texana	A		D	A		X			D	A					X	X	D	A	D	A
Coraliophaga coraliophaga															X					
Rupellaria typicum																X				L
Petricola pholadiformis		D		A	X			X	D							X				D
Anatina canaliculata	D		D	D	X				D						X		D		D	
Anatina lineata															X		D		A	D
Mactra brasiliana		D		A						D					X	X	D	D	D	A
Mulinia lateralis		D		A					D	A					X		D	A	A	A
Rangia cuneata		A		A						A						X	D	A	D	D
Spisula solidissima raveneli															X		D		D	
Donax texasiana	D	A			X		X		D						X		D	D	A	D
Tagelus divisus																X		L		L
Tagelus gibbus		D		A		X			D	D					X	X	D	D	D	A
Abra aequalis	D								A	D					X			L	A	L
Cumingia tellinoides		D								D					X					
Semele proficua			D												X	X		L		L
Semele purpurescens										D					X	X				D
Macoma constricta				A					D	D					X		D	D	D	D
Macoma mitchelli				A						A						X		A		A
Macoma tageliformis		D														X	D			D
Tellidora cristata									A						X			L	D	L
Tellina alternata	D		A			X			A						X		D	L	A	L
Tellina lineata									D						X	X		D		
Tellina versicolor		D							D						X		A		A	L
Ensis minor		A		A											X	X	D	A	D	A
Corbula conradi									D	A								A		
Barnea costata	D			A		X	X		D	D					X	X	D	D	D	D
Pholas campechiensis				D				X							X		D		D	
Martesia smithii										A								A		A
Lyonsia floridana	D									A						X		A		
Pandora trilineata					X				D	A					X	X		A	D	A
Periploma inaequalis				D					D						X	X	D	L	A	L
CEPHALOPODA																				
Spirula spirula	D		D	D	X				D						X		D		D	
Loliguncula brevis					A	A	X				A	A	A					A	A	A
Loligo peali							X				A						A		A	
Octopus vulgaris							X				A	A	A	A						
AMPHINEURA																				
Ischnochiton papillosa									A	A								A		A

quite abundant in upper San Antonio Bay, but in 1951, no living examples were found. It is not certain, however, whether the living populations of *Rangia* and *Littoridina* have disappeared as a result of increased salinities, or from some other causes.

III. POSSIBLE PALEOECOLOGICAL INTERPRETATIONS

Observations of the sort noted in this paper should be of some value in analyzing the environments in which fossil assemblages existed during Pleistocene and possibly Pliocene times. Puffer and Emerson (1953) observed that the faunal aggregations present during extended periods of low salinity appear to differ from those present during periods of high salinity. As they indicated, large numbers of *Ostrea equestris* on top of the reefs of *Crassostrea virginica* indicate increased salinities. In fossil assemblages, the echinoderms, corals, and the Gulf mollusks now found living in the bays may also constitute valid criteria for recognizing essentially marine conditions in former estuarine waters. Associated with these faunal changes indicative of salinity change is the *Rangia-Littoridina* community of upper San Antonio Bay which evidently disappears under increased salinity conditions. Whereas *Ostrea equestris*, marine mollusks such as *Strombus alatus* Gmelin, *Sinum perspectivum* Say, *Simnia uniplicata* Sowerby, *Tellidora cristata* Recluz, and *Tellina versicolor* Dekay, echinoderms, and corals indicate high salinities of from 30 to 40°oo, the *Rangia-Littoridina* assemblage appears to be a good indicator of very low salinities of from 3 to 8°/oo. Changes in size of certain mollusks also appear to be asssociated with prolonged salinity changes. It has been noted by Ladd (1951), Mitchell (1894), and the author, for example, that *Rangia* attains a far greater size in waters of very low salinity, or in almost fresh water, than it does in more saline waters. From the center of San Antonio Bay to the delta of the Guadalupe River and into the main mouth of the Guadalupe in Mission Lake, *Rangia* becomes progressively larger. This relationship may exist because the juveniles are killed by the more saline water before attaining the normal size attained in nearly fresh water. A similar relationship of size to salinity exists in the pelecypod, *Mulinia lateralis*, although the salinity range is far greater (from 5 to at least 60°/oo). Examples of *Mulinia* from the hypersaline lagoon, Laguna Madre, south Texas, all tend to be much smaller than those from the waters of more normal salinity further north.

As previously mentioned, *C. virginica* appears to undergo considerable variation in shell shape with extreme variation in salinity. A similar change was also noted by Hedgpeth (1953 and personal communication) in a small oyster reef situated in the hypersaline waters of the Laguna Madre near Port Isabel, Texas. It is also possible that the oysters undergo this change in shell shape when the salinity varies intensely in either direction.

It has also been observed by Gunter (1938) that the oyster assumes a different shape under varying sediment conditions. Oysters which become buried under mud during rapid sedimentation will grow very long and narrow in order to maintain their water intake above the surface of the bottom. If oysters of this shape (commonly called "coon" oysters) are found in fossil assemblages, it might be assumed that the reef had undergone rapid silting. A somewhat similar phenomenon has been observed in Copano Bay during periods of very low salinity, when oysters supposedly grew too rapidly and formed dense clusters of long thin individuals. In the case of the silting of oysters, the dense clusters are not formed. The dense clustering and elongation of the individuals in the cluster may be related to food supply, which may become more abundant at low salinities. It may be noted here that the "coon" oysters differ somewhat in appearance from those affected by the prolonged high salinities, in that in the "coon" oyster the whole shell is elongated and thin rather than only the lips.

SUMMARY

1.—Published and unpublished salinity values from the bays and open Gulf of Mexico of the central Texas coast from 1922 until 1953 indicate that during the recent six-year drought the salinities have become much higher than prior to 1948. Previous studies have shown that salinities in the bays generally rose above 34°/oo in the summer months, but during most of the year ranged from 5 to $25^{\circ}/_{oo}$. From 1948 to 1953, salinities increased to well over $36^{\circ}/_{oo}$ and at times above $40^{\circ}/_{oo}$, without any appreciable decrease in the winter months.

2.—Comparisons of the total monthly discharge from the rivers emptying into these bays, with the total monthly rainfall from representative areas in the drainage basin of the rivers for all years of salinity data, indicate that when river discharge and associated rainfall were high, the salinities were low for corresponding months; and conversely, when discharge and rainfall were low (as during the last six years) salinities were high.

3.—With the increase in salinity, the oysters in the Texas bays were observed to take on different shell characteristics such as thin, sharp, highly colored, and crenulated valves.

4.—During low-salinity years, the reefs were composed primarily of *Crassostrea virginica*, a typically euryhaline species, whereas with the increase in salinities, there was a corresponding increase in the number of small marine oysters, *Ostrea equestris*, a species characteristic of waters of higher salinity. In 1952, it was observed that well over half of the spat-size oysters were *Ostrea equestris.*

5.—During the period of extended high salinity in Aransas Bay, many organisms were collected which had not been previously noted from this area. The organisms most indicative of high salinities were the echinoderms and coelenterates. Many species of gastropods and pelecypods, which had been confined to the open Gulf and inlets, were found throughout Aransas and Copano bays. There was also a corresponding decrease and disappearance of low-salinity mollusks in San Antonio Bay which had formerly been abundant. Whether this disappearance of low-salinity mollusks from the now high-salinity San Antonio Bay is a direct result of salinity increase is also not known.

6.—Penaeus setiferus, the commercial white shrimp, virtually disappeared from the bays with the increase in salinity, while *Callinectes danae*, a more or less open Gulf crab, became extremely abundant in the bays.

7.—Such observations may have some significance to the paleoecologist in interpreting environmental changes associated with changes in the fossil assemblages.

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Reprinted from Evolution, Vol. IX, No. 1, March, 1955
Printed in U. S. A.

THE ROLE OF ONTOGENY IN SYSTEMATICS AND EVOLUTION [1]

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Received August 2, 1954

Introduction

In recent decades the basically morphological fields of ontogeny, systematics, and evolution have been brought into closer alliance by the broadly unifying concepts of genetics. Modern genetics has not only given us some understanding of the mechanisms of evolution, but also has demonstrated clearly the hereditary nature of the characteristics of all developmental periods. All growth stages and all normal developmental processes of an organism are controlled by a single genetic system and are subject to evolutionary changes. These established genetic concepts have far-reaching importance to systematics, for they provide a sound basis for the use of characters from the full range of developmental stages in classification and in the study of evolution. Research on early developmental stages has always emphasized morphology, and a vast amount of routine descriptive work is still to be done, but the value of these basic descriptive data in the solution of problems in life histories and classification has already been demonstrated on a limited scale. There is need for much wider application of ontogenetic data in such problems, and the present paper discusses some of the principles and procedures of interpretation in this field.

Developmental Systematics

The idea that developmental characters may be a source of material for evolutionary studies dates at least from the period of intense interest in descriptive embryology in the nineteenth century. Much theory and speculation have resulted, especially around the topic of recapitulation. The long popularity of this theory has somewhat overshadowed the ideas of Von Baer (see de Beer, 1951), which were essentially sound by present standards though they preceded the modern expansion of genetics. Von Baer stressed the value of comparative studies on the same growth stages of different species, rather than the search for ancestral adult characters in embryonic stages. Some of the more recent authors who have reviewed the recapitulation question and its history are Shumway (1932), Meyer (1935), Holmes (1944), and Case (1950). Additional problems of development in relation to evolution were discussed by Haldane (1932), Hubbs (1926, 1940), Waddington (1941), Gregory (1946), and de Beer (1951).

The study of taxonomy in terms of natural populations rather than of a few specimens in the laboratory is now quite standard, but there is equal need for analysis in terms of the whole ontogeny rather than of a single stage. In older taxonomic practice, notably in the vertebrates, it was generally customary to restrict study to the characters of the mature adult. Ordinarily, of course, these characters are the easiest to determine and are the most convenient base for routine taxonomic work. The life histories and early developmental stages of many groups of animals are difficult to decipher and are very incompletely known, and it is impractical to postpone a study indefinitely in the hope that all of the desired data may be forthcoming. Never-

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[1] Contribution from the Scripps Institution of Oceanography, New Series, No. 755.

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theless, the full characterization of a species comprises all of its genetically regulated attributes throughout its ontogeny and thus, ideally, judgment in taxonomy and evolution should be based on a unified summary of the data obtainable from the entire developmental pattern rather than on any single stage. The validity of a taxonomic judgment that is deliberately based only on the final, adult stage, when ontogenetic data are available, compares with the validity of a phylogenetic judgment that is based only on the extant species, without regard to the known fossil history of the group.

Developmental patterns differ widely in different groups of animals. Among the vertebrates, the fishes and amphibians are exceptionally favorable for combined studies in development and systematics. Although not all species of the lower vertebrates have a well-defined free-living larva, they all present developmental problems of one sort or another than can be studied to advantage by systematic methods. Development is relatively direct and uncomplicated in some fishes and amphibians. In these, growth proceeds simply and smoothly and there are few definable stages, thus relatively few opportunities for complications to arise from independent evolution of early developmental characters. But even in these species the embryonic period reveals similarities and differences in growth characteristics (in pigment cells and color pattern development, modifications of the fins, etc.) that are of taxonomic value. In most of the species, the ontogeny includes a distinct larval stage and a consequent period of metamorphosis. In these forms, the complications both in the ontogeny itself and in its evolutionary potentialities are greatly increased.

Genetics has provided a valid explanation both for the occurrence and for the limitations of independent evolution in different developmental stages. Structures that comprise the basic morphological pattern or *Bauplan* of a species are subject to extensive coordinated modifications; a major change in a basic structure (e.g., in number of somites) produces evident effects in all stages in which that structure is visibly represented. Characters that are phenotypically expressed in only one stage of development (e.g., the barbels of flyingfish larvae) can undergo evolutionary changes which alter that developmental stage but have no apparent effect on other stages (although they are, of course, carried in the genotype). Independent changes of this nature account for many well-known examples in which the larvae of two species differ more widely than do the adults, or the larvae of two obviously different species are scarcely separable. The existence of independent evolutionary changes in different stages of development emphasizes the need for study of the entire life cycle. Evolutionary interpretations that are based on fragmentary data can be equally misleading whether the specimens are adults or larvae. The wider the general background and experience in systematics, then, the more effectively ontogenetic data can be used in this field.

From the knowledge that development is genetically controlled, one can infer that the same basic evolutionary phenomena apply to early developmental characters and to adult characters. As in the adult stage, some features of the developmental pattern may be extremely stable and persistent in geologically-old phyletic lines and hence of great value as indicators of relationships. In contrast, other developmental characters may be very plastic and subject to elaborate secondary modifications and selective adjustments that have little bearing on the main lines of developmental evolution. This rather flexible evolutionary picture complicates the task of interpreting ontogeny, but it is simply another facet of variability and is a logical extrapolation from well-established evolutionary principles. Such hypotheses can be tested readily through integrated study of the characteristics of the entire ontogenetic cycle.

PATTERNS OF DEVELOPMENT, LARVAL TYPES

The interpretation of the relative systematic values of different ontogenetic variables is a challenging problem. In the taxonomic study of development, one attempts to distinguish between various levels of evolutionary significance in developmental characters, and to learn how environmental factors may modify the expression of these characters. The objectives and the methods are essentially the same as they are in taxonomic studies on the adult stage.

If the basic developmental pattern of a particular taxonomic group can be defined it then provides a reliable point of reference for analyzing the nature, significance, and possible mode of derivation of secondary developmental variations and adaptations in that group. Clear definition of developmental patterns and larval types that have broad phylogenetic value makes it possible to use ontogenetic characters to help determine the relationships of puzzling groups in which the adult stage is so specialized that the characters on which the taxonomist usually depends are obscured. The developmental pattern of *Sacculina* is a classic example from the invertebrates. Such knowledge also permits successful prediction of the general characteristics of development of poorly known species on the basis of known data from related species. In evolution, as in other fields, successful prediction is an important test of the validity of inferences.

Few large-scale studies on developmental systematics of the lower vertebrates have been reported, but from the results already obtained come the theoretical premises which are discussed here. For example, the complex mass of known details on the morphology and variation of frog tadpoles resolves into a simple, orderly, and conventional pattern of basic and secondary evolutionary trends (Orton, 1953). The frogs are a particularly fortunate example, for this richly varied amphibian group is small enough to be studied conveniently in its entirety, and the tadpole is an unusually distinctive type of larva and has undergone very elaborate evolutionary modifications. From these studies on a small taxonomic group come new clues that may be helpful in recognizing and defining patterns of developmental evolution in the fishes, a vastly larger and more complicated group.

Although much general descriptive work has already been published on early developmental stages of fishes, this group is so large and diversified that ontogenetic studies are still confined principally to gathering the necessary background of morphological data. This aspect of developmental study is far from completion, but it is already possible to use the available data in a wide variety of ways in the systematics of fishes. The importance of detecting and interpreting the morphological effects of direct development provides a good example.

Most evolutionary changes that modify larval characters affect the larval structures themselves, but changes that have their primary effect on egg size and yolk supply may carry secondarily a considerable alteration of embryonic and larval phenotype, that often results in the more or less extensive suppression of larval characters. In its extreme form, this is the familiar "direct development," a modification that exhibits a high degree of independent evolution in the amphibians (Lutz, 1947; Orton, 1949), and almost certainly in the fishes as well. Recognition of the occurrence and effects of direct development in the fishes is one of the preliminary steps in sorting out the various kinds of trends in developmental evolution in this vast group. The characteristics that direct development shows in the amphibians are a useful guide to help determine whether distinctive developmental characters in large-egged fishes may be correlated primarily with evolution in egg size (hence, with direct development) rather than primarily with actual evolution of larval structures.

Clues to the original or "normal" larval type in large-egged fishes may best be sought among small-egged relatives of the group in question. Three families of salmonoid fishes, the Osmeridae (true smelts), Coregonidae (whitefishes), and Salmonidae (salmons), provide an instructive example and a suggested interpretation. These fishes are closely related and indeed have often been lumped together in a single family. Typically, the smelts have small eggs and the larva (e.g., in *Mallotus villosus* and *Osmerus mordax*) has the general form, pigmentation, and compressed, transparent musculature that characterize the leptocephalus-like larva of clupeoid fishes (herrings, sardines, etc.). The salmons have large eggs and slow embryonic development, and hatch in an advanced condition followed by a prolonged yolk-bearing stage that transforms directly into the juvenile. The whitefishes have eggs of moderate size and their developmental product is intermediate between the small pelagic larva of the smelts and the large, yolk-bearing "alevin" larva of the salmons.

The salmonoids and the clupeoids, together with certain other groups of fishes, comprise the large and varied Order Isospondyli. Study of the developmental pattern of the salmons against the broad background of isospondylous fishes as a whole, suggests strongly that the well-known and widely-studied developmental characters of the salmons constitute a clear example of secondary direct development that is comparable to many such cases in the amphibians. It seems probable that the herring-like larva of the smelts is the basic larval type in the salmonoid fishes as a group, and, furthermore, that it is the normal type of larva to be expected in both the clupeoids and the salmonoids unless it is masked by secondary modifications of egg and embryonic characters. Thus, it seems apparent that the salmons skip the expected larval stage as a consequence of greatly increased yolk supply, and that the whitefishes have followed the same trend but with a less extreme result.

Larval characters that are suppressed phenotypically as a consequence of direct development are not necessarily lost genetically, but may be carried in the genotype for long periods without outward manifestation. Cornman (1943) discussed the genetics of comparable situations, with examples from problems of real or ostensible reversal of evolution. Applying this genetic background to the present problem, it can be postulated that if the Salmonidae, with direct development, gave rise to a new family of fishes in which the egg size and yolk supply were reduced and a small pelagic larval stage thus restored to the ontogeny, the genetic potentialities for the clupeoid type of larva would again find phenotypic expression, and the characters of the restored larval stage in the new group would be essentially like those of the basic clupeoid type rather than of a totally new and different type of larva.

The complexities of this example illustrate the wide scope of developmental systematics and its bearing on major evolutionary investigations in the fishes. Information on basic patterns of development and basic types of larvae in fishes should help to solve many puzzling problems at various levels, from population questions and species studies to work on the higher categories of classification.

ONTOGENY AND THE SPECIES PROBLEM

In older taxonomic work, descriptions of species and the general understanding of the category of species were based on limited morphological criteria, largely or entirely from adult (or presumed adult) specimens. In modern work it has become increasingly evident that study of the species concept requires a much broader biological approach. Developmental studies contribute substantially to the solution of systematic problems at the species level, and the developmental viewpoint can help to clarify the species concept itself.

The species is the highest category that applies to "a kind" of animal; all higher levels are, by definition, group categories —groups of related kinds of organisms (see Hubbs, 1943). The species has an important and apparently very real evolutionary status. It denotes populations that have achieved sufficient uniformity in developmental pattern, in adult morphology, and in other biological characteristics, and sufficient stability in geological time, to establish and hold an area of distribution, which may become very extensive. The genetic processes that bring a population to the specific level of differentiation are probably basically similar in most groups of organisms, but these processes have different results in different groups, in respect to ontogeny and to the structures that are produced. The criteria that distinguish all species in all groups of organisms are, therefore, neither of the same nature nor of the same magnitude. Species of fishes cannot be equated exactly with species of flies or of sunflowers; species of fishes are not all separated from each other in exactly equal degree. This is apparent from comparison of adult stages of different groups of fishes, but it is even more obvious when the diverse life history patterns of groups (such as the sardines and the embiotocid fishes) are compared. Consequently, it should occasion no surprise that even though the category of species has a clear general meaning, it cannot be rigidly defined. Taxonomic categories acquire their greatest significance when they are studied in relation to the characters of particular groups of organisms (cf. Rollins' "species standard" idea, 1953), especially when these studies encompass the entire life cycle.

It is a well-known principle in taxonomy and paleontology that a given character does not necessarily confer the same categorical rank on all species that possess it. There is no universal criterion that always, automatically, denotes "species," "genus," or other category. The taxonomic value of a character depends on its stability and on the nature of its variability, and these qualities may differ greatly in different groups or even between related species in the same group. This general principle was derived chiefly from studies on mature specimens, but it is readily demonstrable in early growth stages as well, for a particular developmental character may have quite different values in different groups. Viviparity, with highly specialized embryonic modifications, is a constant family character in the Embiotocidae (surfperches), but in certain other families of fishes, e.g., the Scorpaenidae (scorpionfishes) and the Clinidae (klipfishes), some species are live-bearers and some are egg-layers. Just as species are not all precisely equivalent, neither are all characters of uniformly predictable taxonomic meaning. The significance of the characters of any growth stage must be weighted comparatively, and sound judgment in systematics therefore depends to a considerable degree on wide experience and intuitive thinking.

The flyingfishes, family Exocoetidae, afford a convenient example of the contribution of ontogeny toward solution of revisionary problems in systematics, especially problems that involve difficult questions of species definition. The literature and current classification of the flyingfishes are unusually confused; there are about 150 nominate forms, but it is probable that fewer than one-third are valid. The species are moderately variable, but for the group as a whole the total range of variation in known adult characters falls within rather narrow limits. As a consequence, some species that are clearly different, such as *Cypselurus exsiliens* and *Cypselurus heterurus*, show extensive overlap and even (in some individuals) full duplication in such characters as fin-ray and scale counts. The rigorous environment and habits of these fishes appear to favor selection toward a conservative uniformity in adult characters, and it is unusually difficult to determine not only the relationships of a given species but even what constitutes a species, if one relies solely on the adult stage. Fortunately, the ontogeny is unusually well suited for taxonomic study (Bruun, 1935; Breder, 1938; Hubbs and Kampa, 1946). The eggs and embryonic stages are large enough so that their distinctive characters are easily studied, and the larval stage shows conspicuous interspecific differences both in its special structures and in the complex sequence of its color pattern development. *Exocoetus volitans* and *Exocoetus monocirrhus,* for example, are very difficult to distinguish in the adult stage, and their synonymies are so thoroughly entangled that they probably can never be entirely clarified. Yet, the young stages of these two species are so dissimilar that they could scarcely be confused. The larval period is unusually protracted in many or most of the flyingfishes. The larger larvae have often been mistaken for adults, and a considerable number of the new names have been based on larvae, unwittingly or otherwise. Characters of species groups are especially well-defined and conspicuous in the larvae, and preliminary study suggests that phenotypic divergence in these fishes is in reality greatest prior to maturity. For an understanding of exocoetid taxonomy and interrelationships, it will be necessary to integrate data from the full range of developmental stages of each species. Indeed, for nomenclatorial as well as for biological reasons, it will be impossible to monograph this group successfully without full use of ontogenetic data. The names that were based on larvae cannot be allocated to the correct synonymy until the species to which each of these named larvae belongs is determined. A number of the larval names definitely have priority and others probably do. In the flyingfishes, and in other groups with similar problems, it is abundantly clear that accurate species diagnosis and species grouping depend on extensive knowledge of the full life cycle.

Ontogeny and the Higher Categories

Most students follow the concept that evolutionary processes operate at the lowest taxonomic levels, from species down through subspecies to unnamed races and local populations. Heavy concentration of study on these productive ranks has largely diverted attention from the higher group categories. Interest in the evolutionary significance of these higher taxonomic units is, however, a natural corollary of developmental systematics because of the necessarily broad scope of the latter field. The developmental specialist works with wide ranges of ontogenetic variability, especially if the group under study has an elaborate larval stage, for the range of difference between stages in the development of the same individual is much greater than that which separates two related species at the same stage of development. The wide interpretation of intraspecific variability that this work imposes, and the need for rather extensive concurrent study of adult characters for background, preadapt the developmental systematist to an interest in the application of ontogenetic data to some of the more inclusive problems of classification and phylogeny, such as the origin of new higher categories.

Goldschmidt (1940) and de Beer (1951) traced the historical background of a long-held, though often vaguely-expressed, idea that rapid large steps in evolution may be initiated by modifications that affect early developmental processes. This idea suggests that if a genetic modification affects the course of development only in its late stages, most of the basic anatomy is already established and only lesser (though perhaps conspicuous) details can be altered. But, if the effects of the modification are evident from the early embryo onward, there is opportunity for very extensive alterations both in the ontogeny as a whole and in the resulting adult stage. Changes of this nature could sharply increase the rate of evolution and greatly hasten the establishment of a new bauplan. Evidence from paleontology, reviewed by Simpson (1953), indicates that the rate of evolution is commonly accelerated during the early fossil history of lines that (as we know from their later history) led to the differentiation of new higher categories.

The most extensive evolutionary results of modified ontogeny can appear in groups that have a relatively complicated developmental pattern, particularly if it includes a highly differentiated larval stage. De Beer (1951) discussed in detail the potential importance of ontogenetic changes and cited examples of various kinds of developmental modifications that might have significant evolutionary results. He treated at considerable length the idea of origin of new major groups by neoteny from highly evolved larvae. It has been speculated that even the chordates may have originated by neoteny; the notochord and somites may have been larval specializations in the ancestral stock (see Gregory, 1946, 1951; de Beer, 1951). Neoteny is, however, not the only means by which developmental modifications may have major evolutionary consequences. The entire ontogeny as a unit may shift relatively rapidly (in geological time) to a new structural plan. It has been suggested that a change of this nature, the extreme shortening of the vertebral column in both larva and adult, precipitated the origin of the frogs (Orton, 1953).

There is much evidence to support the concept of evolution of developmental processes, but Goldschmidt's extension of this topic (1940, 1952) has somewhat obscured the important basic idea. He believes not only that evolutionary modifications which affect early developmental processes can lead to new species and new higher categories but also that these modifications are of an entirely different genetic nature than those that produce new subspecies. He maintains that mutation and selection function only at the subspecific level or below, and would be too small in effect and too slow in operation to account for the production of new higher categories or even of new species. He considers subspecies to be genetic and evolutionary blind alleys that do not give rise to new species. This differs sharply from the view held by most geneticists (see Dobzhansky, 1951) and systematists that all evolutionary trends and changes of whatever level of complexity result from the same repertoire of genetic processes, and that any established population is, theoretically, a potential ancestral stock for further speciation. The hypothesis that different kinds of evolutionary processes operate at different taxonomic levels appears to hinge on insufficient consideration of the paleontological record and of the way in which taxonomic categories are used by systematists. A new higher category does not originate as such. The unit that arises in evolution is a new definable population, a new kind of animal. The initial change must take place in the genetic structure of members of a natural population, whatever the nature or direction or ultimate evolutionary consequences of that change may be. As Simpson (1953) points out, the original mutant would still be a member of the parent species. It may be helpful to compare the use of terms and ideas in this case with that in a similar situation of common occurrence in descriptive taxonomy. When a systematist "discovers a new order of fishes," what he actually discovers is a new species, i.e., a new kind of fish, that differs sufficiently from other known species of fishes to warrant, in his experienced judgement, definition of a new series of group categories up to ordinal rank to contain it.

The vast majority of new species probably evolve by means of very gradual, small changes in details of development, structure, and function—changes that conservatively keep within the framework of an established bauplan in ontogeny as well as in adult structure, and lead to new higher categories only very slowly, if at all. In contrast, new species that are produced relatively rapidly (in the geological sense) by genetic changes that profoundly affect key developmental processes, and thereby provide the morphological and functional basis for a new structural plan, are the most likely precursors of rapidly-evolving new groups that ultimately attain high categorical status. Simpson (1953) emphasizes that a major change of this nature offers new adaptive possibilities that may have a high selective advantage, and Muller (1949) stresses the probable greater importance of selective factors than of mutation rates in this kind of evolutionary situation. Since the findings of genetics indicate that heritable changes can modify the phenotype at any stage of ontogeny, genetic evolutionary change itself appears to be an example of variability over a continuous scale. The two extremes of evolutionary pattern discussed above differ in degree but not in kind, for they could be connected by a full range of intermediates.

Summary and Conclusions

Certain basic problems and principles pertaining to the role of ontogeny in systematics and evolution are reviewed, and their application to the fishes is discussed. In recent years the unifying principle of genetic inheritance has drawn these fields closer together. Demonstration of the genetic nature of developmental characters, hence their validity as evolutionary material, is particularly important. The same basic principles of evolution apply to the adult stage and to earlier stages of development. Characters that are unique to particular developmental stages in the same species can evolve independently, and these independent trends show that reliance on fragmentary data from any single stage in ontogeny can be equally misleading in taxonomy. Carefully coordinated study of the entire ontogeny of each species is, therefore, greatly needed.

A key problem in developmental systematics concerns the distinction between various levels of evolutionary significance in different developmental characters, and we are guided toward its solution by the well-established principles derived from studies on adult stages of organisms. Data on basic developmental patterns and basic larval types of major groups can help to solve taxonomic problems at all levels. These basic developmental criteria provide reliable points of reference for interpreting complex secondary trends, and aid in making taxonomic decisions when the adult characters are too specialized to be dependable indicators of relationships.

The developmental approach to systematics also helps to clarify the species concept, for certain of the basic difficulties of the latter are best understood in terms of a broad, ontogenetic species definition. The very unequal degrees of difference between species, and the variable taxonomic value of the same character in different groups of species, gain clarity from the wider perspective of developmental study. The flyingfishes provide an outstanding example of the importance of developmental work in the untangling of difficult taxonomic groups.

Ontogeny also contributes toward understanding the origin and evolution of higher categories. It has long been held that geologically-rapid, major evolutionary progress can result from genetic changes that affect key developmental processes, especially in groups that have a complicated life cycle. A new structural plan can evolve by neoteny or by coordinated changes that alter both the adult and the early stages. New species that result from such rapid and drastic developmental evolution are more likely to lead to establishment of new higher categories than are new species that are produced much more slowly by selection of very small mutations. These two extremes of difference in species formation can be connected by a full range of intermediates, and there is no need to postulate, as Goldschmidt did, separate kinds of genetic processes for the evolution of different categories.

Integrated studies on the entire developmental pattern can be a great stimulus to achievement in the fields of systematics and phylogeny, and should bring us closer to a real understanding of the interrelationships and evolution of living organisms.

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Extrait des ANNALES DE GÉOPHYSIQUE
Tome 11, fascicule 1. — Janvier-Mars 1955.

EVIDENCE FROM THE ROTATION OF THE EARTH (*)

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For a brief survey of the subject we consider the scheme in Table 1. The x- and y-components of a vector representing the angular velocity of the earth determine the displacement of the pole of instantaneous rotation along the meridians of Greenwich and 90° E. Changes in these components constitute a " wobble " of the earth. Fluctuations in the z-component (through the mean north pole) correspond to changes in the length of day (l.o.d.). The wobble is determined from precise measurements of latitude whereas the l.o.d. problem requires precise measurements of longitude.

TABLE I.

The Spectrum of Irregular Fluctuations in the Rotation of the Earth.

	Annual	Decade	Millenia	Geologic
x, y	International latitude service 10 feet Air mass	< 15 feet Motion in core (?) and sea level	?	Fossil magnetism Thousands of miles (?) ?
z	Crystal clocks 1 ms Winds	Modern eclipses 1 ms Motion in core	Ancient eclipses 10 ms Tidal friction and sea level	?

Legend : The upper part refers to the wobble component, the lower part to changes in the length of day. For each rectangle, the first item (in capitals) refers to the method for observing the fluctuation. The second line refers to the order of magnitude of the observed effect. The wobble terms are in units of feet of displacement of the pole of rotation (or very nearly in units of $0'',01$ of the tilt of the axis of instantaneous rotation). The z-term is in milliseconds of change in the length of day (roughly parts per hundred million). The third line gives what is believed to be the principal cause or causes.

(*) Communication présentée à la réunion commune sur la Physique du Noyau Terrestre, tenue à Rome le 20-9-54, sous la présidence de Sir Edward Bullard, par les Associations Internationales de Séismologie et Physique de l'Intérieur de la Terre " et de " Magnétisme et Elect icité Terrestres ".

(1) Contribution from the Scripps Institution of Oceanography, New Series. N° 756.

In Table 1, the four columns represent different orders in the frequency spectrum of irregularities in the rotation of the earth. We do not imply that any decisive changes in the spectrum occur from column to column ; rather these are distinguished by differences in observational technique. Measurements under the auspices of the International Latitude Service give information about the x, y-spectrum over periods of half a year to a few decades, although the long periods are uncertain because different coordinates were used at different times, and the relationships have not been clearly defined. Detection of annual fluctuations in the l.o.d. has recently been made possible by comparison of astronomic time with clock time as inferred from quartz-crystal clocks. Fluctuations over decades or longer have been known for some time from observation of eclipses. The evidence for decade oscillations now consists of irregularities in the longitudes of the Sun, Moon, Mercury and Venus, and of eclipses of Jupiters's satellites. Changes in the l.o.d. since Egyptian time have been inferred from a few well observed ancient eclipses of the Sun and Moon.

Any explanation of observed changes in the earth's rotation must satisfy the following restraints :

1. Conservation of angular momentum.
2. Conservation of mass.
3. The deduced wobble *and* l.o.d. must be consistent with observations.
4. Rates of displacement and acceleration of mass must be " reasonable "
5. The inferred processes must be reversible for some observed changes and must continue in the same direction for others.

Analyses in accordance with the above considerations indicate that the causes of the observed fluctuations are varied. It appears that the decade changes in l.o.d. are largely due to motion in the core, whereas more superficial events are responsible for the shorter and longer periods. As these superficial events provide the background noise for any study of motion in the core by astronomic means, they deserve a short discussion here.

The annual wobble is principally the result of seasonal shifts in air mass from the Iceland and Aleutian low pressure areas to the Siberian high pressure area [1]. Atmospheric events may be responsible also for intermittently exciting the Eulerian nutation (Chandler motion) with a period of 14 months. It is not known to what extent shifting air masses may excite x, y-terms of longer period, but in view of the sharpness of the annual peak it is not likely that the atmosphere contributes heavily to the decade terms. On the other hand, melting of ice caps may be a significant factor. The astronomic evidence precludes a shift in the position of the pole of rotation by more than about 15 feet between 1900 and 1950, and there is some weak evidence of a shift by 10 feet towards 40° W. Such a shift would be caused by a 3 cm rise in sea level due to melting of the Greenland Ice cap [2]. This involves 10^{19} gm of melted ice in fifty years. Recent French expeditions to Greenland indicate melting by 10^{17} gm per year [3]. The two figures are not far out of line, and we may therefore expect a significant contribution to the decade wobble from short period climatic fluctuations. This is important to our subject, because it is in this frequency band that the motion in the core is likely to be significant. Nothing is known about changes in the x, y-components over periods longer than centuries, but shorter than those of the geologic time scale.

Now let us turn to changes in the l.o.d. It is fairly clear that the annual term is largely the result of changing winds [4]. (There is also a regular semiannual term related to the bodily tides.) It is significant that changing winds (transfer of angular momentum between the atmosphere and the solid earth), though not necessarily negligible [5, 6], play a relatively minor role in the wobble of the earth. This indicates a tendency toward zonal symmetry of fluid motions on a rotating body, which may apply to motion of the fluid core.

For periods longer than one year the contribution from the atmosphere must be quite small, far too small to account for the observed variations in the decade band [7]. Going now to periods much longer than decades, the observed changes since Egyptian times can best be accounted for by tidal friction [1] plus some decrease in the earth's moment of inertia [8,9]. Such a decrease could result from a rain of mantle iron into the core, as proposed by Urey [9]. We have shown [2] that it is also consistent with a lowering in sea level by a few meters since Egyptian times, and a corresponding growth of ice caps. A change of sea level by this amount has been inferred by many investigators from evidence based on the study of ancient beach lines.

We come now to the heart of the problem, the high activity in the decade range of the z-term (Table 1). Changes in winds, air mass and ocean mass, which are so important in other parts of the spectrum, simply won't do here. There is barely a chance that an oscillating plastic flow of mantle material might account for the observed fluctuations in the l.o.d. But the required velocity of subcrustal flow is about twenty times larger than that indicated by the observed rate of isostatic adjustment. Moreover, it is difficult to conceive of any geophysical mechanism which could bring about a poleward flux of mantle material for twenty years and a reverse flux for the next twenty years. Following what Sir Edward Bullard has called a Sherlock Holmes procedure, eliminating one possibility after another, we have come to the elementary conclusion that the source must be deep-seated and probably due to transfer of angular momentum between core and mantle [7].

There is, moreover, positive evidence for this. One would expect that fluctuations in the rate of westward drift of the earth's magnetic field, if it is an indication of the relative rotation between mantle and outer core, should be correlated with fluctuations in the rotation of the crust and mantle. The relationship can be derived if we assume conservation of angular momentum of the earth as a whole, and some law of electromagnetic coupling between core and mantle. Taking Bullard's [10] simplified two layer fluid core, we derived the relation [7]

$$\tau = -10\,\Delta(wd)$$

where τ is the departure from the mean length of day, in milliseconds, and $\Delta\,(wd)$ the departure from the mean westward drift of the Earth's magnetic field, in degrees per decade. The above equation relates measurements at astronomic observatories to those at magnetic observatories. Observations are available since 1890, and they are encouraging. They agree with regard to sign and order of magnitude, though the numerical constant in the above formula appears to be too large. This value is based on the assumption that the time constant of electromagnetic coupling is short compared to the period of fluctuations. The time constant varies inversely with the electric conductivity in the mantle. It was thought only a few years ago that the mantle conductivity was 10^{-10} emu giving a time constant of 300 years, and that marked changes in the l.o.d. occured quite suddenly possibly in a year or so. This would rule out the above hypothesis. But recent evaluations of the electric conductivity of the mantle near the core yield values of more than 10^{-9} emu, and hence a time constant of the order of decades. At the same time Brouwer's [8] recent analysis of the astronomic data indicates that the changes in the l.o.d. are much less abrupt. Thus a discrepancy by two orders of magnitude has evaporated, and there are no grave difficulties in relating quantitatively the magnetic and astronomic data.

The quantitative comparison was undertaken by Vestine [11]. Between 1890 and 1910 the westward drift diminished, whereas the l.o.d. increased. After 1910 the reverse took place. One cycle is of course not much to go by, but additional data will be slow in coming The numerical evaluation leads to about -3 instead of -10 milliseconds /degree per decade in the above equation, but this discrepancy can be accounted for by the uncertainties in the time constant and other aspects of the model.

Vestine [11] has also suggested that the observed north-south component of the drift of the magnetic field may be related to the decade wobble. However, as he himself emphasizes, the melting of the Greenland ice caps offers a possible explanation of the observed change in the x, y-terms. In any case the small magnitudes of these changes relatives to those in the z-term requires a high degree of axial symmetry in the *variations* of the fluid core motion. This implies that the mean motion is largely zonal.

Recent studies of the remanent magnetism of ancient sedimentary rocks suggest that during the last billion years the magnetic poles have wandered over

10 000 km. This would imply that the axis of rotation has been equally unstable. The dynamic implications are not clear to us.

We may summarize the astronomic evidence concerning motions in the fluid core as follows :

1. The only satisfactory explanation of the observed changes over a decade or so in the length of day is that there are rather large variations in the fluid motions of the core.

2. The deduced variations agree in sign and magnitude with those inferred from the westward drift of the magnetic field. The combined evidence indicates a differential velocity between core and mantle of 10-20 km /year near the boundary at the equator. The slippage zone must be sufficiently thin so that the drift in the detailed features of the non-dipole field can be observed at the surface. This may place a useful upper limit on the viscosity in the core. For example, if the slippage zone is 300 km thick and the period is taken as 20 years, the kinematic viscosity is 4×10^6 cm^2 sec^{-1}. The agreement between the magnetic and astronomic data supports Bullard's conclusion that the viscous coupling between core and mantle must be much less than the electromagnetic coupling.

3. The motion in the core is largely zonal.

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Imprimé par Taffin-Lefort, à Lille (France). — *Published in France.*

THE
AMERICAN NATURALIST

Vol. LXXXIX July-August, 1955 No. 847

SOME ASPECTS OF ECOLOGY AND ONTOGENY IN THE FISHES AND AMPHIBIANS[1]

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Although long tradition combines the study of amphibians and reptiles into one field, these two vertebrate classes are usually treated entirely separately, in actual practice, even when both are discussed in the same paper. Comparative papers on amphibians and reptiles are rare, except for those that inquire into basic evolutionary problems from the paleontological viewpoint. Typically, we specialize in details and overlook the broadly comparative problems that cross departmental and taxonomic lines. Perhaps discussion of some of the opportunities offered by a different and less familiar combination of taxonomic groups can make the advantages of interdepartmental study more tangible. The fishes and amphibians invite such comparative study, for these two classes present some important common problems in life history and evolutionary biology.

Effective comparison of fish and amphibian life histories is somewhat hampered by numerical and ecological differences. The Recent amphibians are remnants of a once very large and complex group, but the Recent fishes represent a continuing great diversification of a long-dominant group. Furthermore, the fishes are aquatic throughout life, but most amphibians have, in addition, both the advantages and the problems of terrestrial life during part of their ontogeny. Within the limits imposed by such differences, however, much can be learned from comparative studies on life history patterns and on developmental characters, in relation to the varied ecological situations that these animals face.

We commonly base ecological and distributional studies on the adult stage only, and overlook the possibility that the relative success or failure of a species may be determined largely by events that affect its early developmental stages, rather than its more conspicuous adult. The critical importance of survival rate in early stages is recognized most clearly by fishery biologists, who are concerned with size of population of commercial

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[1] Read in symposium on "Problems in Ecology of Amphibians and Reptiles," AAAS, Berkeley, December, 1954. Slightly expanded for publication. Contribution from the Scripps Institution of Oceanography, New Series, No. 757.

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species and with the contribution that each successive year-class makes to that population. The fishes and amphibians are excellent materials for comparative study of environmental conditions that influence the place of a particular species in the fauna through their effects on critical stages in its ontogeny. Ecological life history studies on these animals could be considered from several different viewpoints, for ecology is an integrative science that draws its data from many fields. The present paper reviews some of the evolutionary background of life history study, and then discusses some ecological and developmental problems in the fishes and amphibians, centered chiefly around the varying importance of the larval stage in dispersal and gene exchange.

THE EVOLUTIONARY BASIS OF LIFE HISTORY CHARACTERS

Evolution involves complex interactions between environmental selection on the one hand and genetic potentialities and limitations on the other. These controls do not restrict their operation to the adult characters, but affect every aspect of the life cycle.

Paleontology can reveal very little of the actual course of life history evolution, but comparative study of many living groups with diverse relationships gives much indirect evidence of evolutionary trends in developmental characters, breeding habits, physiological characters, general behavior, etc. It is easier to recognize that these are valid topics for evolutionary study if we keep in mind the well-established principles that the entire ontogeny of an individual is a unit governed by a single genetic system, and that variation and change can modify either the whole ontogeny or any part of it.

The first amphibians were doubtless little more than a population of aberrant crossopterygian fishes. For some time the prospective new group and its close relatives probably retained a rather similar genetic makeup in most respects, and continued to face similar ecological situations and to share common life history characters. Further evolution widened the gap between them, not only in adult characters but in the entire ontogeny. Meanwhile, the precursors of the main lines of teleost evolution also became established. Their subsequent evolution has been very elaborate in all aspects of morphology and development, and is still inadequately understood. The taxonomy and evolution of the fishes and amphibians are highly complex subjects, and need evidence from all possible sources, including developmental characters.

THE ROLE OF THE LARVAL STAGE IN DISPERSAL AND GENE EXCHANGE

The importance of the larval stage in the general biology of the species and in the evolution of groups is both complex and variable. For example, in many invertebrates, especially marine groups, the dispersal of the species depends on pelagic larvae. In some other groups, notably some of the insects, the larva is a sedentary feeding and growing stage, and the adult is restricted to a brief, mobile, reproductive period at the end of a long larval life. In some cases the larva confers no obvious advantage on the species, and its continuance in the ontogeny is perhaps little more than an ancient genetic tradition.

Even in a relatively restricted group, such as the lower vertebrates, the actual function of the larva in the life of the species varies widely. In the non-parasitic brook lampreys, for example, the larva is a prolonged feeding and growing stage, and the adult has become reduced to a terminal, non-feeding, reproductive stage. In many of the non-migratory marine fishes distribution depends largely on pelagic eggs and larvae, for the adults settle in limited territories and do not wander far after maturity. The fishes and amphibians offer many opportunities for comparative studies on the role of the larval stage in maintaining populations or in promoting gene exchange between populations.

Freshwater fishes

In freshwater fishes, geographic spread is guided largely by the pattern of lakes and stream systems. All developmental stages are aquatic and have access to essentially the same migration routes. In general, it is likely that the adult is usually the chief agent in dispersal and gene exchange, except perhaps in large lakes where pelagic larvae would foster mixing of populations, and in crowded streams in which accidental hybridization may occur.

A substantial amount of the known natural hybridization of freshwater fishes, especially in rivers and streams, may result not from direct interspecific matings but accidentally from the drift of freshly spawned eggs and sperm, especially where ecological modifications have restricted the available spawning sites to small overcrowded areas that are used simultaneously by two or more species (work by Carl L. Hubbs and collaborators; e.g., Hubbs and Miller, 1953). Although these situations perhaps usually result from man-made ecological changes, they could certainly also stem from natural physiographic disturbances. Hubbs (in several papers) has suggested that the apparent greater frequency of natural hybridization of freshwater fishes than of marine forms is probably due in part to the greater opportunities for chance mixing of eggs and sperm of related species in freshwater streams, and to the less stable ecological conditions in fresh waters.

The known eggs of most freshwater fishes are demersal. They are either attached to some supporting object, or are heavy enough to sink to the bottom, or are buried in sand or gravel. Eggs of some freshwater forms, although technically demersal, are only slightly heavier than water and are non-adhesive. These eggs are subject to action by currents, which may roll them about or keep them more or less suspended, and may even carry them a considerable distance before hatching takes place. Examples include some of the cyprinids, and the striped bass, *Roccus saxatilis*. The striped bass is a diadromous fish, but it is appropriate to mention its freshwater eggs here. A few freshwater fishes are known to have true pelagic eggs, free-floating at or near the surface. These include some of the gouramies, the eggs of which can float at the surface independent of support by the bubble nest. This has long been known. An account by Ryder (1886) was apparently overlooked by Eigenmann, who stated in his widely quoted paper (1909) that he knew of no freshwater pelagic eggs. At least one freshwater clupeoid, *Amphiodon alosoides*, has pelagic eggs (Sprules, 1949), and additional examples can be expected. In general, however, true pelagic eggs are uncommon in freshwater fishes, and are not known to provide conspicuous opportunities to spread the species into new territory. The occurrence of pelagic eggs in certain freshwater clupeoids is probably chiefly of genetic rather than ecological significance, i.e., retention of the type of egg that characterizes most of the marine members of the group.

Freshwater fishes display a rather limited range of known larval specializations. This apparent limitation in variability is probably partly explainable on ecological grounds. The amphibians must bridge the gap between larva and adult with both a morphological and an ecological metamorphosis, but in the freshwater fishes the larva and the adult occupy essentially the same kinds of environments. Hence, in the latter group there has been much less pressure on the larva to "make good" in a sharply different ecological niche, as a critical link in the success or failure of the species. The fishes as a whole do have ample genetic capacity for larval variability, as is well shown by the great range of developmental specializations in the marine fishes.

Amphibians

Amphibians that are completely aquatic in all developmental stages have patterns of dispersal and opportunities for gene exchange similar to those of freshwater fishes. Speciation and distribution in these animals are influenced by the geography and ecology of drainage systems, and by similar factors that reflect restricted environment and limited avenues for movement. In these fully aquatic forms the larva is perhaps neither more nor less important than the adult as an agent in distribution and population stability.

By far the commonest and best-known life cycle in the amphibians comprises aquatic egg and larval stages and terrestrial adult stage. Within this general framework the details of ecology, breeding habits, and developmental characters vary widely. The role of the larva in extending the geographic or genetic importance of a particular species varies with the taxonomic group and with the general ecological circumstances. Larvae that live in ponds or temporary pools are closely confined, and hence wandering and gene exchange in these species are necessarily functions of the post-metamorphic juveniles or of the adults. Climatic and taxonomic variables and physiological requirements influence the relative importance of larva and adult in the dispersal of different species that breed along interconnecting waterways rather than in isolated pools. In a favorable climate, an adaptable species may do considerable overland wandering in the adult stage, resulting in significant mixing of local colonies. A form less capable of overland travel, or living in a climate less favorable for it, would disperse mainly along the home stream system. Here, perhaps larva and adult would be equally effective in dispersal. If there have been significant differences of this sort in mode of dispersal, their influence on evolution might be discernible in present-day patterns of distribution and speciation. A careful study of North American amphibians from this viewpoint might be profitable.

The greater evolutionary success of the frogs than of the salamanders (comparing them at the ordinal level) is certainly related in part to the much greater capacity of the frogs for genetic variability in developmental characters. Tadpoles probably do not often lead their species into extensive new areas, but larval evolution and adaptation have kept pace successfully with adult wanderings into new areas and adaptations to peculiar habitats. The distributional significance of the tadpole is therefore chiefly indirect. A non-migratory species that has a confined larval stage cannot live in a particular area unless both its larva and its adult can live there. Highly successful evolution in developmental characters has allowed the frogs to succeed in many situations that would be closed to them if the group as a whole were too inflexible in developmental requirements (Orton, 1953).

Tadpoles that are highly specialized for peculiar ecological conditions are known from many parts of the world. There is extensive adaptive radiation in larval characters not only in the frogs as a whole, but also within many of the families and even within some of the larger genera. Equally important is the extensive convergent evolution through which larvae of unrelated forms have secondarily evolved very similar adaptations. For example, many kinds of tadpoles are modified for life in swift mountain brooks. The more extreme kinds have a flattened head and body, long flat snout, greatly enlarged mouthparts, thick heavy tail muscles, and reduced tail fins. Convergence toward this morphological and ecological type is conspicuously duplicated by unrelated larvae in at least six families, but the precise details (especially of the mouthparts) differ widely and in general retain basic characters of the particular group from which the specialized larva is derived. Many examples of gradations in complexity between this extreme specialization and the more ordinary tadpole format are known. Stream adaptation in tadpoles is a very attractive ecological and evolutionary problem, and greatly needs further study.

Larval adaptation helps a species to live under special conditions, but it might also ultimately restrict the species to those conditions. If extreme specialization in tadpoles is genetically irreversible, it is conceivable that many groups of frogs might eventually specialize themselves into extinction through modification of their larvae into extreme end-forms, unable to cope with subsequent ecological changes. Here, larval ecology involves the basic genetic question of reversibility of evolution, another very attractive problem that is beyond the scope of this paper.

One of the most successful ontogenetic specializations in the frogs—direct development—has nearly eliminated the larva as a recognizable stage. Amphibians that have direct development skip the free-living aquatic tadpole and are terrestrial at all stages. The factors that modify their distribution approach those of any group of strictly terrestrial animals. Much has been published on the developmental morphology and general ecology of amphibians with direct development (e.g., Lutz, 1947, 1948; Orton, 1949, 1951), but little on population studies that relate this modified ontogeny to the over-all economy of the particular species. In recent work on a leptodactylid genus, Syrrhophus, (reported at the Pullman AAAS meeting, June, 1954) Jameson found the adult frogs to have small home ranges, but the newly hatched terrestrial young wander much more widely and are evidently the stage responsible for most of the dispersal and gene exchange in these frogs.

The factors that govern direct development in amphibians provide an interesting field for study and speculation. Perhaps the most obvious and most-often stated point is that direct development frees the species from dependence on open water for its eggs and larvae, and the species can then live successfully in areas that lack suitable aquatic habitats. Direct development is, however, not a single culminating achievement in the frogs, but is an independent specialization in many unrelated lines. In some regions (some of the West Indies, some Pacific islands) amphibians with direct development are the dominant, or the only, amphibians. But direct development is by no means confined to species that live in areas which do not provide normal habitats for an aquatic tadpole. A species that develops in terrestrial sites is freed from larval competition and thus gains a selective advantage even in regions that are well provided with swamps or streams. For example, the very large and complex genus Eleutherodactylus and certain other closely related genera form an important part of the frog fauna throughout the neotropics, and so far as their life histories are known they all have direct development. That larval competition can be a real factor in the success of a species is obvious to anyone who has watched the dense tadpole populations in small ponds. The successful establishment and spread of colonies of the accidentally-introduced *Eleutherodactylus ricordi planirostris* in Florida, studied by Goin (1947), is a striking example of the ability of a frog with direct development to compete in a region that is saturated with a very rich native fauna of frogs with aquatic larvae.

The taxonomy of early developmental characters has been studied much more extensively in the amphibians than in the freshwater fishes. This would be surprising enough if the two groups were of nearly the same size and importance, but the better-studied amphibians are a much smaller group and have a minimum economic importance. The rich opportunities for correlated developmental and taxonomic studies on freshwater fishes have been much neglected. This peculiar hiatus in knowledge stands out especially sharply to those who enter ichthyology after previous training and experience in herpetology. It illustrates the need for greater awareness of problems and successful methods in other fields in addition to one's own speciality.

Diadromous fishes

In the freshwater fishes and the amphibians, the role of the larva in dispersal and gene exchange is often minor or indirect. But in the diadromous fishes, and especially in the marine fishes, the situation changes and the larva assumes a greater direct significance as a factor in population dynamics.

Migratory species in many groups of fishes regularly spend different stages of their life cycle in waters that contrast in salinity or in other physico-chemical factors. An ecological classification of all these fishes would involve virtually all conceivable intermediate patterns of migration and combinations of habitats. In order to simplify general reference to such fishes, Myers (1949) proposed the new term "diadromous" to apply to any or all fishes that undergo a breeding migration into waters of different salinity.

The best-known diadromous fishes are two groups that display extremes of difference in migratory pattern: the salmonids with marine adults that enter freshwater streams to spawn and have large eggs and a large, yolk-bearing larva ("alevin"); and the freshwater eels that go to the sea to spawn and have pelagic eggs and a peculiar leptocephalus larva.

The significance of the larva in the distribution of diadromous fishes varies, depending on the direction and ecological details of its migration, and on the characters of its taxonomic group. The marine salmonids that hatch in fresh water and mature in the sea typically return to their home stream for spawning. Downstream migration of the larvae is rather strictly channeled, and any effective range extension would be done primarily by the adults, through errors in navigation on the return spawning run. These conditions minimize effective mixing of populations, and favor local differentiation of genetically isolated stocks. In other groups of fishes that enter fresh water to spawn, the migration and mixing of stocks in different developmental stages may be more complicated and less conducive to population stability. For example, the striped bass runs a variable distance upriver into fresh water to spawn, but its semi-pelagic eggs may be carried downstream for a considerable distance, and may enter brackish water or even sea water before hatching (Raney, 1952). This fish is now under intensive study along the Atlantic, and in the San Francisco Bay region (where it has been introduced), to determine the extent of the coastwise migrations of adults and young, and the possible importance of migration in maintaining or mixing populations.

Problems of population dispersal are somewhat different in fishes that have the reverse pattern of migration, i.e., spawning at sea and maturing in fresh water. If sea spawning occurs in estuaries or close inshore, there would be limited opportunity for gene exchange by means of drifting eggs or larvae, and in such cases localized differentiation associated with river systems might be the rule. If spawning takes place far offshore, the genetic as well as the geographic situation could be quite different. If all the freshwater eels of the western north Atlantic drainage go to the same general area in the sea to spawn, with no segregation in time or space, there is theoretically opportunity for a very thorough mixing of each generation that could keep the entire eel population relatively homogeneous, with no tendency to split into localized races. Johannes Schmidt found such uniformity to characterize the European eel, but this problem has apparently never been investigated in the American eel. A long larval migration through the open sea to reach the adult habitat puts a heavier burden on the eel larva than does the relatively simple downstream migration of the salmonid larva. There are still many unanswered questions on this aspect of the life history of our freshwater eel.

Marine fishes

In the marine fishes the larval stage attains its greatest importance, among the vertebrates, as an agent in dispersal and gene exchange. Two major factors in marine ecology that influence distribution are: the huge continuous space that is theoretically available in the sea, and the widespread occurrence of free-floating pelagic eggs and larvae, which comprise part of the vast community of the marine plankton. The dispersal of pelagic early stages of marine animals has been compared aptly with the wind-borne dispersal of the pollen and seeds of terrestrial plants (Garstang, cited by Hardy, 1954).

The adventures of the pelagic egg and larva are very important to successful completion of the life cycle of the individual, in addition to their potential importance in extending the geographic range of the species. Plankton life is highly competitive. It is heavily dominated by invertebrates, and fish eggs and larvae comprise only a very small part of it. In some groups of fishes both the egg and the larva are pelagic (e.g., sardines and mackerels); in others, the egg is demersal but the larva is pelagic (e.g., blennies and gobies). The enormous production and enormous waste of pelagic eggs and larvae have been commented on by many writers. Norman estimated that a 21½ pound cod produces 6½ million small pelagic eggs; in contrast, a 20 pound salmon produces only about 17,000 large demersal eggs. Johannes Schmidt estimated a Mola to contain 300 million eggs. The plankton drifts with the ocean currents, and is affected by many additional factors in the physical environment. These conditions vary greatly from time to time, and in some years oceanographic events may be very unfavorable for the survival of certain species, through mass failure of the larvae to reach areas or conditions that are needed in their later development. As a consequence, the relative success of year-classes may differ within very wide limits, especially in species that produce very high numbers of eggs. Ahlstrom (1954) pointed out that: "The initial strength of a year-class is dependent on the amount of spawning; its subsequent strength, on survival after spawning. In actual numbers of individuals, a year-class at its inception is many times as large as the total adult population.... the history of each year-class is one of rapid decrease in numbers." He estimated the survival rate in the 1950 and 1951 year-classes of the Pacific sardine as one larva surviving to the 21 mm. stage per 1000 eggs spawned. Sette (1943) estimated survival in the 1932 year-class of the Atlantic mackerel as between one and ten larvae surviving to the 50 mm. stage per million eggs spawned. He considered this an abnormally low survival rate for this species, resulting from unusually adverse conditions in that season.

Various authors, interested in the effectiveness of pelagic young as distributing agents, have investigated the duration of these stages in relation to the direction and distance they may be carried before leaving the plankton. Regan (1916) suggested that coastal species that occur in different areas widely separated by open sea probably have a long pelagic stage; in general, coastal forms that have a short pelagic stage would not be dispersed as widely and are likely to have more restricted ranges. Larval dispersal is, of course, not the sole determinant of range size or range continuity. Other factors, such as length of residence of the group in the area, also modify distribution. Bonnet (1939) studied the drift of pelagic stages of the Atlantic cod, which spawns in winter at very low temperatures. He summarized that eggs spawned off Massachusetts at 3°C hatch 23 days later, and the larvae remain drifting in the plankton for seven days, before settling to the bottom, making a total time of about 30 days in the plankton. The estimated drift of four miles per day would take them about 120 miles, and would land the settling larvae on the edge of Georges Bank, a favorable bottom area for young cod.

Clark Hubbs (1953) discussed the extensive distribution of Labrisomus, a genus of clinid blennies that is represented in the eastern Pacific and on both the American and African shores of the Atlantic. It has the longest pelagic larval stage of any clinid known to him, and he suggested that it probably reached Africa by trans-Atlantic migration in the larval stage. Williams (1954) treated the bearing of larval distribution on a complicated subspecies problem in Gibbonsia, another clinid genus in the eastern Pacific. Here both allopatric and sympatric subspecies had been described. He noted that the allopatric forms differ in meristic characters, which are usually fixed in early developmental stages, and concluded that these forms probably constitute definite genetic populations. The described sympatric forms, however, differ only in proportions and other characters that can be modified by the environment very late in development. He postulated that these described sympatric forms are not separate genetic stocks but are derived from a single ecologically-widespread population that becomes thoroughly mixed during the pelagic larval stage, and that the proportional and other differences develop after the individual larvae have settled in a variety of different environments.

These examples indicate but a few of the kinds of problems in the field of larval ecology of marine fishes. The value of such study is manifold, for it contributes toward better understanding of the systematics and evolution of the fishes, as well as toward practical knowledge of biological factors that control productivity of an important part of man's food supply.

SUMMARY AND CONCLUSIONS

In the freshwater fishes and the amphibians, the role of the larva in distribution and gene exchange is often minor or indirect; but in the diadromous fishes, and especially in the marine fishes, the larva assumes a greater direct significance as a factor in dispersal and population dynamics. The sharpest contrasts are between the frogs and the marine fishes. In the frogs the outstanding distributional significance of the larva lies in its genetic variability, which permits adaptation to a very wide range of ecological conditions. This high degree of larval adaptability has helped the frogs to distribute themselves very widely, and it has certainly been an important factor in the greater evolutionary success of the frogs compared with the salamanders. In the marine fishes the larva commonly has a very direct role in dispersal of the species, through a more or less prolonged stay in the drifting plankton.

The fishes and amphibians share many basic problems that can be studied effectively by comparison and by interchange of ideas. Progress in the study of either of these groups can suggest the means for substantial advance in the other, not only in ecological topics but in other problems concerning ontogeny. For example: (1) Patterns of larval evolution in the frogs are virtually a blueprint to guide the study of developmental characters in the fishes. Although the problems are much more complex in the fishes, they appear to involve essentially the same principles. (2) The year-class concept, which is so important in population studies on marine fishes, could be applied effectively on amphibians and reptiles. It would give both a broader understanding of population ecology in these animals, and a greater realization of the importance of the whole ontogeny as the unit in the study of species problems.

Early developmental stages of the fishes and amphibians show many modifications that are more or less obviously adaptive to the environment of the particular species, and these characters offer many interesting ecological problems. In addition to ecological study, however, there is need for extensive investigation of the taxonomic and phylogenetic stability of these characters, and the nature of their evolutionary trends.

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Geol. Soc. America
p. 221–236, 11 figs.

Special Paper 62, 1955
Made in U. S. A.

Pelagic Sediments of the Pacific*

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ABSTRACT

Sedimentary deposition in the Pacific Ocean is largely influenced by: (1) the great size of the ocean and the relatively small influx of river water; (2) high seismic and volcanic activity, especially in the marginal zone; (3) deep water characterized by relatively high alkalinity and high concentrations of silicate and phosphates; (4) well-developed equatorial current system resulting in high plankton production near the equator in the East Pacific; (5) trenches and other barriers around the margins partially protecting the central regions from influx of coarse continental materials.

The area covered by red clay is both relatively and absolutely larger than in the other oceans, mainly because of the greath depths of the North Pacific Basin. Calcareous oozes are particularly extensive in the South Pacific but occur generally at lesser depths than in the Atlantic. Characteristic of the Pacific are large areas of siliceous oozes. Radiolarian ooze borders the northern fringe of the equatorial calcareous zone that underlies waters of high organic productivity. Diatom ooze forms bands in the northern Pacific and in the Antarctic Ocean.

Chemical analyses indicate differences in the composition of some older and younger clays. The former are richer in Mn, Fe, and P relative to Ni, Ti, and Al respectively. The well-known high radioactivity of the recent pelagic clays is associated with the authigenic zeolite, phillipsite. A little quartz silt is ubiquitous. The iron-titanium and manganese-nickel ratios appear to be indicative of the proportion of hydrogenous matter. High barium and biogenous copper may indicate rapid accumulation and dissolution of organic remains.

Deposits possibly laid down by slumping and turbidity currents occur under the flat bottom in large areas off the northwest coast of North America, and small "sediment lakes" are found at the bottoms of trenches. Direct evidence, such as graded bedding and mixtures of Quaternary and Tertiary fossils, has been found close to topographic highs in the basins of the Mid-Pacific Mountains, north of Alexa Bank, and between the Marquesas and the Tuamotus.

In most topographic lows the slow deposition appears to be continuous and uniform. Much of the bottom of the Pacific is irregular; even on slight topographic highs, erosion, nondeposition, or greatly reduced deposition is evidenced. Outcrops of Tertiary calcareous oozes have been found on such highs. Unconformities are evident in some cores. Tertiary calcareous oozes occur at depths and in areas where clay is being deposited around them.

Seismic-refraction and reflection profiles suggest sediment thickness of approximately 200 meters in the clay areas and 400 meters beneath the equatorial calcareous oozes. A radiocarbon measurement indicates for the last 14,000 years an average rate of deposition of 3 cm/1000 years in the area of maximum carbonate accumulation below the equatorial divergence. The corresponding rate of deposition of the nonbiogenous components would be about 0.26 cm/1000 years.

INTRODUCTION

The term pelagic sediments (Murray and Renard, 1884, p. 495) is difficult to define briefly or precisely, but we are here considering sediments derived in major part

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* Contribution from the Scripps Institution of Oceanography, New Series, no. 758. This paper is based in part on results of research carried out for the Office of Naval Research and the Bureau of Ships of the Navy Department.

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from particles which settled out or were precipitated from the overlying water column, far from continents and thus without much terrigenous material above clay size. Such sediments generally accumulate slowly and commonly have colors indicating marked oxidation.

The paucity of sedimentary rocks of pelagic origin on the continents only emphasizes the importance of the pelagic sediments to earth science, for the total volume of these sediments laid down during geologic time may have been greater than the present volume of sedimentary rocks in the continental crust. Insofar as the material in pelagic sediments has originated from the erosion of continental rocks, they represent a net loss from the surface of the continents to the deep sea floor.

Moreover, differentiation has apparently occurred. Many workers, including Leith and Mead (1915, p. 59–61) and more recently Kuenen (1950, p. 386–396), have pointed out a seeming discrepancy between the amount of argillaceous sediments in the visible continental crust and the much larger proportion expectable from the igneous rock source. Estimates of average chemical composition by these authors indicate that, except for calcium and magnesium, and perhaps silicon, the major elements derived from weathering of igneous rocks are less abundant in sedimentary rocks of the continents than in the source material. In those cases where this difference does not arise from the uncertainty of average composition for igneous rocks, the deficient elements must have been concentrated either in solution in the sea, as in the case of sodium, or in the deep-sea sediments. This concentration in the pelagic sediments is indicated for manganese and phosphorus. Modern analyses suggest that some minor elements, *e.g.*, nickel and cobalt, are also being concentrated on the deep-sea floor.

At present the preponderant type of pelagic deposition is of sediments high in calcium. On the other hand, sedimentary rocks of the continents apparently contain on the average considerably more calcium than the average igneous rock. A difficulty thus arises in striking a geochemical balance, unless the character of pelagic deposits has changed markedly over the course of geologic time.

In many areas pelagic sediments are accumulating so slowly that cores a few meters long contain a more or less complete sedimentary record of oceanic conditions over hundreds of thousands and even millions of years. These sediments may be thought of as a valuable archive for study of the later history of the earth.

The major problems of pelagic sediments are still far from solution. In this brief paper we can only indicate some of the recent progress and tentative conclusions bearing on these problems.

DISTRIBUTION

The general distribution of pelagic-sediment types on the Pacific Ocean floor is shown in Figure 1. Nearly half the area is covered by clay sediments, an almost equal area is occupied by calcareous oozes, and there are comparatively small bands of diatom and radiolarian ooze. The calcareous deposits are distributed over the relatively shallow bottom, where the rate of dissolution is probably low, and below the Equatorial zone of the East Pacific, where plankton production is high.

Along the northern border of the equatorial biogenous deposits, increasing depth

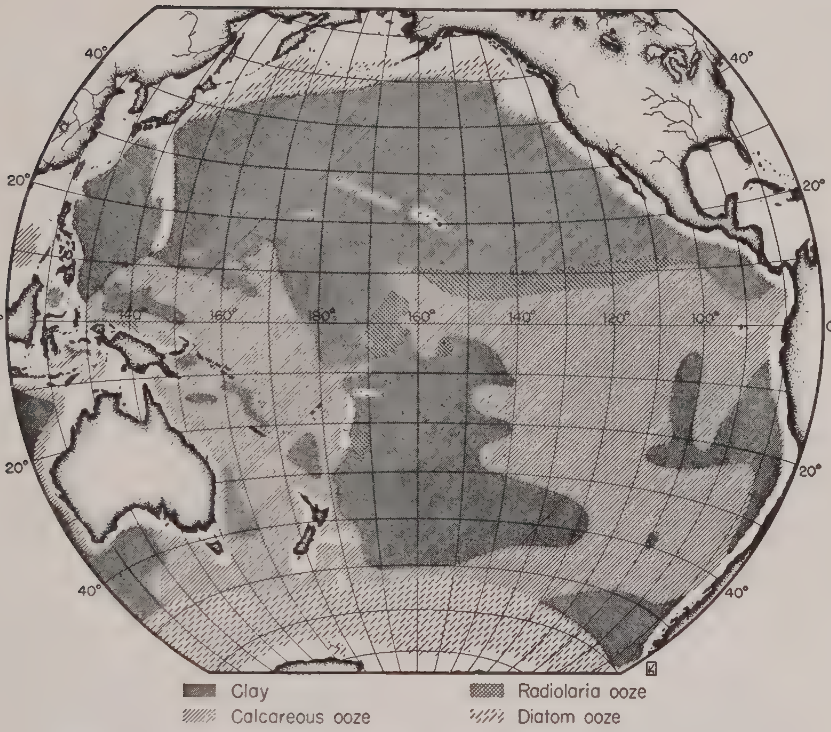

FIGURE 1.—*Distribution of main types of pelagic sediments in the Pacific Ocean*

combines with decreasing productivity to reduce the accumulation of relatively soluble calcareous constituents. The transition zone is marked by a belt of less soluble siliceous ooze with radiolarian and diatom remains.

The relation of the high-latitude bands of diatom ooze to their environment is not yet well understood. Their low-latitude boundary may be determined by a decrease in the rate of plankton production along the Antarctic and Arctic convergences, where low-salinity but cold and dense waters sink beneath the surface (Sverdrup, Johnson, and Fleming, 1942, p. 740). The location of the high-latitude boundary may be due to masking with glacial detritus.

COMPARISON WITH THE ATLANTIC

Pacific pelagic deposits show several conspicuous differences from those of the Atlantic Ocean. The percentage of the bottom area covered by clays (Fig. 1) is nearly twice that of the Atlantic; furthermore, the average carbonate content of the clays is smaller. This is due in part to the larger areas of great depth in the Pacific. It is obvious also (Fig. 2) that the decrease of calcium carbonate with increasing depth is more rapid in the Pacific than in the Atlantic Ocean. No satisfying explanation has been given for this difference. Among factors to be considered are a lower rate of accumulation of clay in the Pacific than in the Atlantic, which would leave the carbonate particles in contact with corrosive bottom waters for a longer

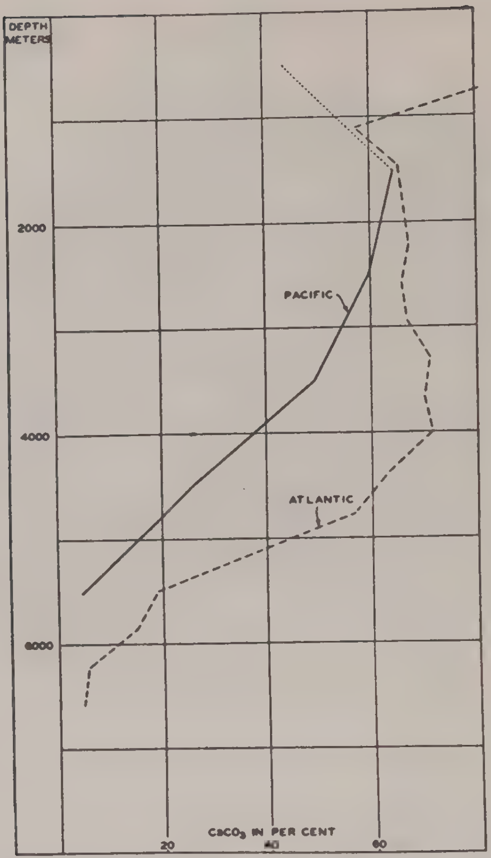

FIGURE 2.—*Relationship between $CaCO_3$ content and depth for pelagic samples*
All depths in Pacific, compared with Atlantic pelagic samples. (From Revelle, 1944)

time; the higher calcium content of the Pacific deep waters (Revelle, 1944, p. 126); and possible differences in the amounts of decomposable organic matter and the resulting production of carbon dioxide in the two oceans.

On the east coast of the Atlantic Ocean, a vast sand desert lies under the trade wind. Consequently, East Atlantic sediments in low northern latitudes show a much higher content of eolian sand and silt than corresponding Pacific sediments.

The clays, especially of the South Pacific, are considerably higher in iron, manganese, and authigenic zeolite than the Atlantic clays. This may be related to the lower rate of accumulation of diluting clay, but also these constituents may accumulate at a higher rate in the Pacific.

Siliceous oozes occur in extensive areas of the Pacific where the dissolution of calcium carbonate outweighs production; they are virtually absent in the Atlantic north of the Antarctic convergence. This difference might be explained by the apparently less rapid clay accumulation in the Pacific. But siliceous skeletal remains commonly form more than 30 per cent of Pacific calcareous oozes and are distinctly

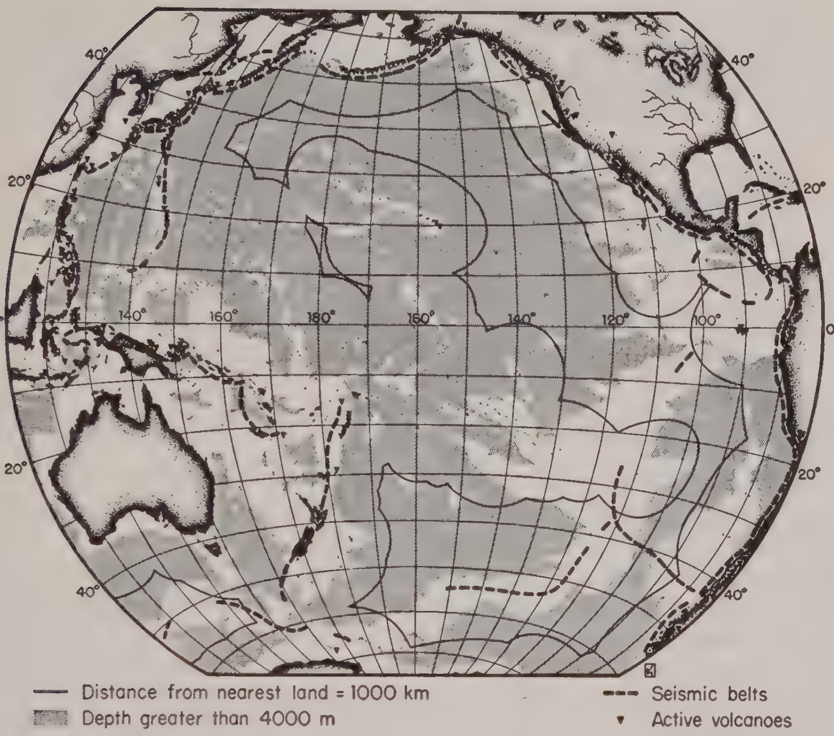

FIGURE 3.—*Main topographic, seismic, and volcanic features of the Pacific*

Dotted area covers depths greater than 4000 m. Seismic zones shown in generalized way by broken lines, volcanoes indicated by triangles. Loci of 1000 km distance from land represented by heavy line.

less in the calcareous oozes of the Atlantic (Correns, 1950, p. 50). We infer that the siliceous skeletons of organisms accumulate on the sea floor at a higher rate in the Pacific than in the Atlantic. The deep and bottom waters, at least in the North Pacific, contain more than four times as much silicate as the corresponding waters of the Atlantic, and considerably more phosphate and nitrate (Sverdrup *et al.*, 1942, p. 241–245). These differences are probably related, in a manner not yet understood, to the difference in the rate of accumulation of siliceous skeletons in the bottom deposits.

The proportion of pyroclastics is generally greater in Pacific sediments than in those of the Atlantic. This, likewise, may be related in part to rates of accumulation of terrigenous clay, though probably it is largely due to greater contributions from adjacent volcanic areas. The extensive volcanism within and around the borders of the Pacific basin, as well as the great seismic activity, are so well known that little discussion is needed here (Fig. 3). The frequency of seamounts (isolated highs of more than 500 fathoms) is very large in parts of the Pacific. Menard (personal communication) has estimated that there are about 2300 seamounts in an area of 2.5 million km^2 off Baja California. Such forms appear to be for the most part volcanic accumulations. Trenches and ridges, near the borders especially, are likewise more

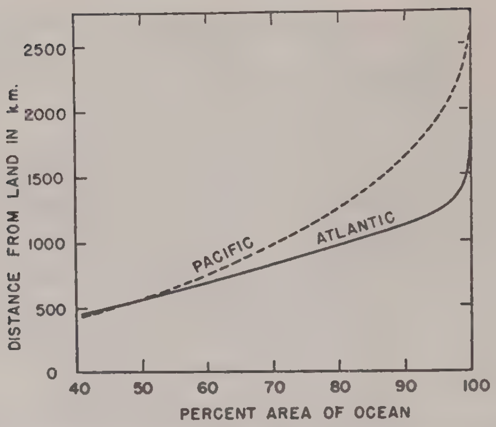

FIGURE 4.—*Cumulative percentage distribution of areas with a given maximum distance from land in the Atlantic and Pacific oceans*

numerous and larger than in other oceans, and may partially protect the central regions from influx of coarse continental material.

In comparison with the Atlantic Ocean, the Pacific is characterized by a small inflow of river water. Reliable figures on the total river discharge into the two oceans are not available, but a qualitative estimate of the difference between them may be obtained from a comparison of drainage areas and of the numbers of large rivers. Some 24 rivers, exceeding 400 km in length, empty into the Pacific, whereas the corresponding number for the Atlantic is more than 100. The difference would be even greater if only those rivers emptying directly into the oceans were considered. The Pacific drainage area, three-quarters of which is located on the Asiatic continent, amounts to approximately 16×10^6 km^2 or one-tenth of the surface area of the Pacific Ocean, while the Atlantic drainage area is approximately 40×10^6 km^2, corresponding to about half of the area of the Atlantic Ocean.

Areas in the Pacific more than 1000 km from land occupy nearly 30 per cent of the ocean (Fig. 4), whereas the corresponding figure for the Atlantic is less than 20 per cent. Areas more than 1500 km from land are practically absent in the Atlantic, but include 10–15 per cent of the Pacific basin. The differences become much greater if islands are not taken into account.

As seen from Figure 3, there are two large regions in the Pacific topographically protected from continental areas and more than 1000 km from any land. Both of these are protected, at least partially, from the American continent by the East Pacific Rise, which also shields the southern area from the Antarctic continent. A barrier to the north of the northern Eupelagic area is probably provided by topographic irregularities in the deep North Pacific.

TURBIDITY-CURRENT DEPOSITS

The characteristics of the Pacific basin described above offer some explanation of the facts that terrigenous influx into pelagic sediments and deposits which can be attributed to turbidity currents are apparently less widespread in the Pacific

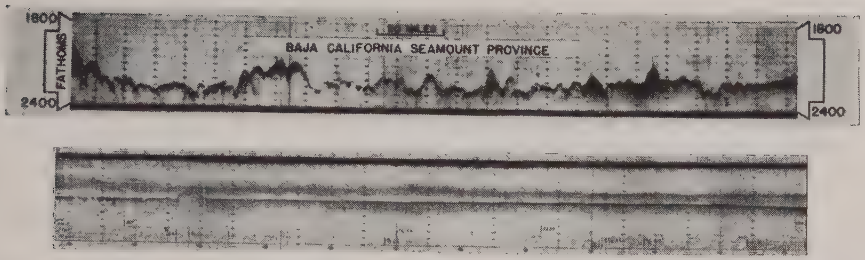

FIGURE 5.—*Fathometer records from the Baja California Seamount Province with extremely irregular bottom, and from the area north of the Mendocino Escarpment, where ridges and seamounts rise above the flat fill of terrigenous sediments*

The vertical scale is the same in both records. Top record is from Menard (1955).

than they are reported to be in the North Atlantic (Ericson, Ewing, and Heezen, 1952, p. 489).

Additional coring may substantiate present evidence indicating that the flat bottoms of certain trenches, such as the Cedros and Acapulco trenches, represent "sediment lakes" filled with and forming catchment troughs for such deposits.

A large area off the northwest coast of North America, not protected by topographic barriers, such as ridges or troughs, appears to have received more extensive turbid-flow deposition (Menard, 1955, p. 239). This region north of the Mendocino Escarpment and between the continental slope and about 155° W. has an extremely flat bottom except for isolated hills and areas of undulating topography (Fig. 5) which are like that of the pelagic area to the south. The few cores from the "unburied" irregular sea floor consist of a highly oxidized buff clay with Radiolaria, typical of the normal North Pacific pelagic-clay regions. Cores from the large expanse of flat bottom are quite different; they consist of a very fluid, gray, silty clay with partially rounded terrigenous sand grains. The presence of iron sulfide in these sediments is also unusual at such depth and distance from land and indicates a greater rate of accumulation than that of the oxidized pelagic clay. Seismic-refraction measurements by R. W. Raitt (personal communication) indicate that the total thickness of a few hundred meters of sediment in this region is not very different from that of the near-by pelagic areas. The gray clay may therefore have accumulated during a relatively brief time—perhaps largely during the Pleistocene.

More isolated and locally derived deposits which clearly indicate slump or turbid-flow deposition have been encountered in a few cores. These show abrupt interruption of deep-water clay deposition by one or more graded beds of shallower-water calcareous materials, with mixed Quaternary and Tertiary (and in places Cretaceous) fossils. These cores were obtained near marked changes in slope, off the Mid-Pacific Mountains, north of Alexa Bank, and between the Marquesas and Tuamotu Islands.

EROSION AND DISCONTINUOUS DEPOSITION

Erosion or nondeposition resulting in the presence of Eocene calcareous ooze at the surface has been described (Hamilton, 1953, p. 211) from flat-topped guyots of the Mid-Pacific Mountains. More surprising is the occurrence at depths of 4500–

5000 meters of middle Tertiary calcareous oozes and clays outcropping on low hills with a relief of 50 to 150 fathoms. The surfaces of these outcrops are commonly furrowed and penetrated by the digging of bottom organisms and coated by a thin uneven layer of clayey material. Elsewhere on the hills, the Tertiary sediments are overlapped by unconsolidated buff clay of variable thickness. Oxygen-isotope ratios from shells of benthonic Foraminifera indicate bottom temperatures of 12°–13°C for two of these mid-Tertiary deposits as contrasted with 1°–2° in the Pleistocene (Emiliani and Edwards, 1953).

Evidence of redistribution of small particles by some form of bottom currents is more widespread. Skeletal remains of Radiolaria (Riedel, 1952, p. 12–15) and coccolithophores (Bramlette and Riedel, 1954, p. 389–390) of Tertiary age in many places are found mixed with modern remains in the upper parts of cores from the North Pacific. These fossils, along with a much larger proportion of matrix clay that is unrecognizable as to age, were perhaps derived and widely distributed from slumps or other erosion on seamounts where Tertiary deposits occur near the surface.

Unconformities of different ages are encountered, and strata with an early Tertiary radiolarian fauna within a few meters of the surface have been found in widely separated cores in the North Pacific clay region. Processes of erosion and redistribution of sediments thus appear to operate on the irregular Pacific floor as on land, even though doubtless at a much reduced rate. Consequently the minor topographic irregularities cannot be too old even if the general rate of sediment accumulation is slower than the rate suggested below.

CHEMICAL COMPOSITION

The chemical composition of pelagic sediments tells much about the geospheres in which the solid particles were formed. Three genetic groups account for the major part of the sediments: hydrogenous solids (Goldberg, 1954, p. 258) formed by inorganic reactions such as oxidation and hydrolysis in the hydrosphere; biogenous matter precipitated in the biopshere; and lithogenous matter solidified in the lithosphere and brought into the pelagic environment from continents, islands, or submarine volcanoes.

The distribution of physico-chemical properties in the open ocean is considerably more uniform than in crystallizing magmas. As a result, the relations between host and guest elements in marine hydrogenous solids are remarkably constant.

Manganese and Nickel: Manganese exists in sea water partly as a negatively charged colloidal hydrous oxide, and consequently scavenges and accumulates marine cationic species, including nickel, cobalt, lead, molybdenum, ytterbium, yttrium, and lanthanum. The marked covariance of manganese and nickel in pelagic clays over a wide range of manganese concentration is shown in Figure 6. A similar correlation is found in manganese nodules. The samples represented in Figure 6 are from the core *Capricorn* 50BP (Fig. 7) in which a discontinuity occurs at 301 cm, separating a buff and gray, plastic clay from friable sediment with abundant zeolite crystals and reddish-brown clay of greater age. The samples from this lower formation are shown as filled circles in the diagram, and obviously are lower in nickel than samples with a corresponding manganese content from the upper for-

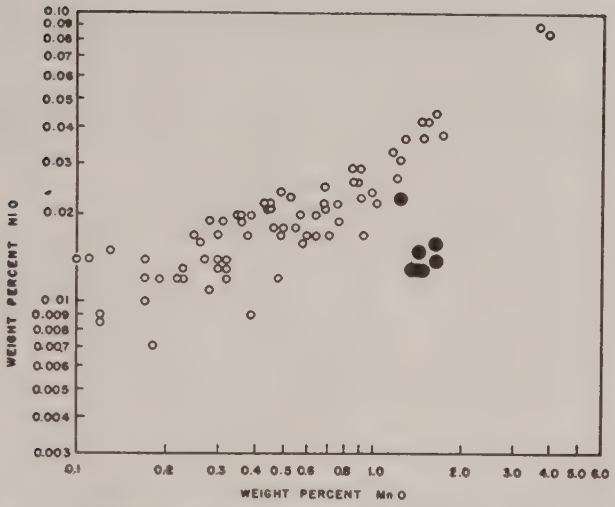

FIGURE 6.—*Relation between manganese and nickel concentrations in core Capricorn 50 BP* Filled circles correspond to samples below the unconformity.

mation. This may indicate a change in composition or rate of accumulation of nonhydrogenous components, a change in relative proportions of dissolved manganese and nickel in the ocean, or a rate change in the scavenging and adsorption processes.

Iron: Iron appears to accommodate titanium, vanadium, and zirconium as guest elements, as a result of the existence in sea water of hydrated ferric oxides which are positively charged and which attract elements prevailing as anions. As with manganese and nickel, the relationship between iron and titanium is markedly different above and below the discontinuity in core *Capricorn* 50 BP (Fig. 8).

Barium: Strikingly high concentrations of barium are found in siliceous sediments fringing the calcareous-ooze areas. Though barium usually ranges between 0.05 and 0.30 per cent in pelagic sediments, the concentration here rises to 1–2 per cent. Barium has never been detected in sea water, but an upper limit of 0.1 part per million has been established by spectroscopic methods. A possible explanation of the high concentration in the siliceous ooze is that minute amounts of barium in the calcareous skeletons of marine plankton become concentrated when calcium carbonate is dissolved, because of the relatively low solubility of barium sulfate. High-barium concentrations would be expected in areas where the rates of both deposition and of dissolution of calcium carbonate are high. The concentration of barium may thus be a measure of the rate of dissolution of calcium carbonate, a variable which has not previously been measurable.

Copper: From the cationic character of copper in sea water, one would expect this element to be scavenged and adsorbed by negatively charged manganese hydroxide colloidal particles. The correlation between manganese and copper in the 400 pelagic clay samples we have investigated is, however, very poor. It appears probable that the striking covariance found between manganese and cationic species other than copper is in the case of copper masked by another independent source of this element. As copper plays an important role in the marine biosphere, this independent source may be organic. Assuming that the lowest average copper concentration in any particular core is entirely due to hydrogenous copper, this quantity can be expressed as a fraction, kMnO, of the manganese concentration. Assuming further that as with nickel, cobalt, lead, molybdenum, yttrium, and ytterbium, the direct proportionality with manganese persists throughout the range of concentrations of this element, the amount of nonhydrogenous copper can be expressed as the difference between total copper and hydrogenous copper (kMnO). As is seen in Figure 9, there is a good correlation between this nonhydrogenous copper and barium, which appears to be almost entirely biogenous and which is

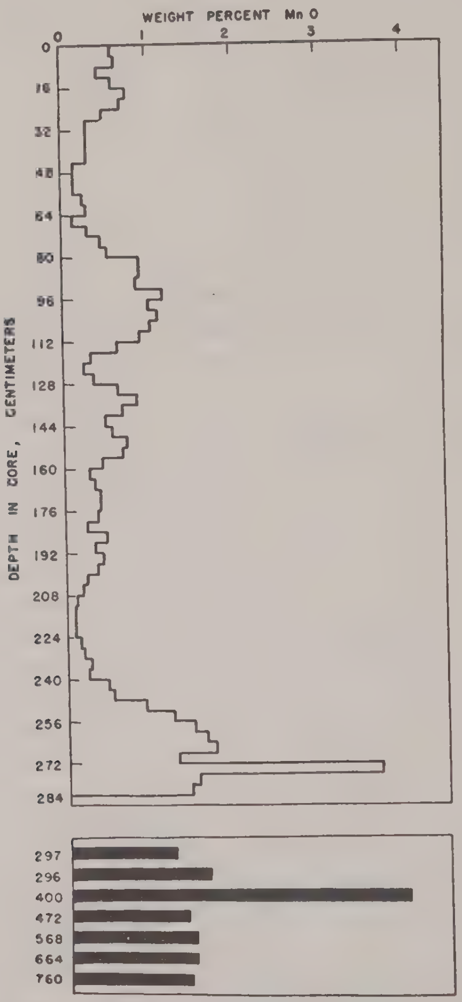

FIGURE 7.—*Manganese concentration as a function of depth in core Capricorn 50 BP* Depth scale is discontinuous below 284 cm.

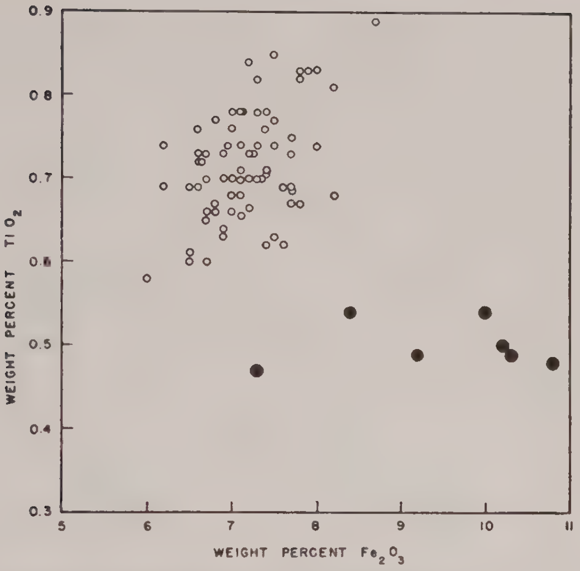

FIGURE 8.—*Relation between concentrations of iron and titanium in core Capricorn 50 BP*

Filled circles correspond to samples below the unconformity.

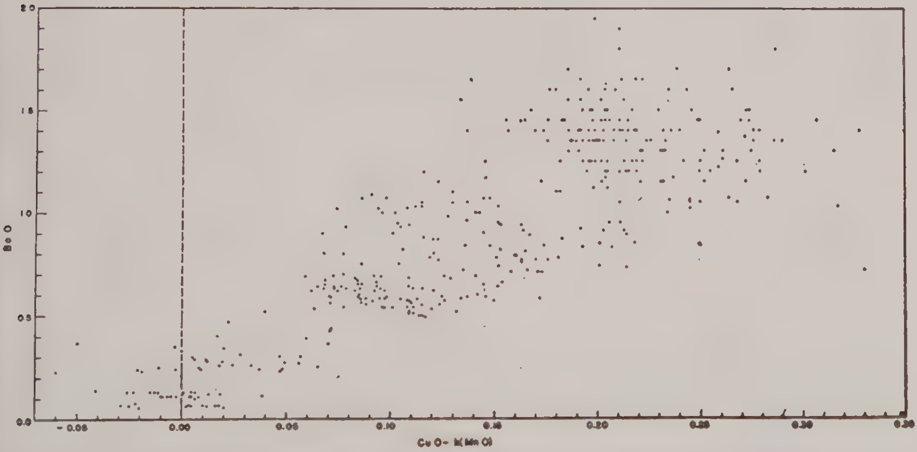

FIGURE 9.—*Relation between barium and recomputed copper in 400 samples of pelagic clay from the North and South Pacific*

The spread, increasing with concentration, is largely due to the logarithmic error of the spectrographic method.

very poorly correlated with total copper or with manganese. This suggests that the pelagic clays contain varying amounts of biogenous copper, in addition to the hydrogenous copper carried by manganese oxides. Furthermore, biogenous copper, which is probably associated with soft parts of organisms or with metabolic end products, may accumulate at a rate generally proportional to the rate of deposition of calcareous shells.

Ionium and Radium: Probably owing to the low rate of accumulation of aluminosilicates in the Pacific, the concentration of ionium and its decay products is generally higher in the pelagic clays of this ocean than in the Atlantic. Most sequences in the cores investigated to date, however, do not show the expected distribution of ionium-supported radium. Instead, the radium content displays irregular maxima and minima throughout the upper strata. Measurements of the gross beta activity on separate mineral fractions indicate that the abnormally occurring radium is bound to the authigenic zeolite phillipsite, and there is a good correlation between the stratigraphic distribution of this mineral and of abnormal beta activity (Fig. 10). These conditions are best explained by diffusion of dissolved radium in all directions from a surface layer where the concentration is high, and subsequent absorption by the zeolite mineral.

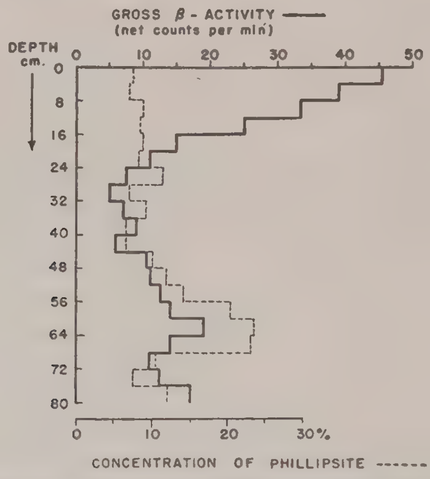

FIGURE 10.—*Gross beta activity and phillipsite concentration as functions of depth in core Capricorn HG23*

LITHOGENOUS MINERALS

Unaltered lithogenous components form only a small fraction of the Pacific pelagic sediments and consist dominantly of pyroclastics and other eolian detrital materials. The contribution of fine-grained volcanic ash is doubtless higher than can yet be established, as much of it is altered to clay minerals, palagonite, and perhaps phillipsite. In the size range 3–10 μ, the lithogenous minerals are dominated by quartz which appears to be rather uniformly distributed throughout the buff pelagic clays in concentrations of 3–5 per cent. Increased proportions of feldspar, augite, and hornblende, in many places in association with volcanic glass, are found near volcanic areas and all over the South Pacific, in the sediments we have examined.

VERTICAL DISTRIBUTION OF CALCIUM CARBONATE

Three types of vertical distribution of calcium carbonate are found in calcareous sediments of the Pacific. Below the equatorial zone of high plankton productivity, calcium carbonate is relatively low near the surface (Fig. 11, type 3) and reaches a

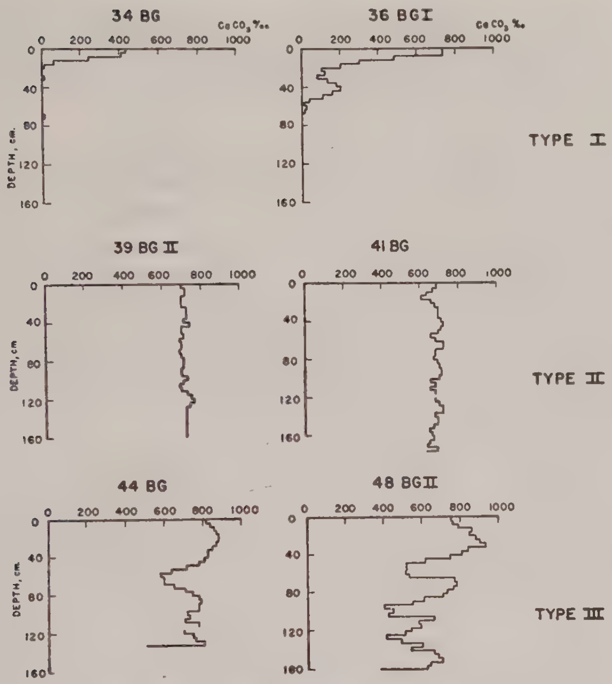

FIGURE 11.—*Three types of calcium carbonate stratification in the East Pacific*

I: East Eupelagic area, south equatorial facies. II: East Pacific Rise. III: East Eupelagic area, equatorial facies ($CaCO_3$ in parts per thousand).

Capricorn Core	Lat.	Long.	Depth, meters
34BG	11°20′S	142°26′W	4500
36BG, I	10°45′S	133°35′W	4480
39BG, II	15°02′S	113°49′W	2890
41BG	13°33′S	113°21′W	2845
44BG	03°42′S	121°03′W	4170
48BG, II	05°49′N	124°03′W	4150

maximum in a stratum which appears to coincide in time with the last glaciation of higher latitudes. The oxygen-isotope distribution in planktonic Foraminifera tests of this high carbonate layer indicates a lower temperature than in the overlying deposit. In other areas, *e.g.*, on the East Pacific Rise, the carbonate content is high and continuous with depth (Fig. 11, type 2), whereas in parts of the South Pacific basins the recent deposit is relatively high in carbonate and overlies a carbonate-poor stratum (Fig. 11, type 1). This last type is somewhat similar to that reported by Schott (1939, p. 405) and others from the Atlantic and Indian oceans. Its occurrence has led to the hypotheses that either the rate of production of Foraminifera near the surface was low during the Ice Ages, or the rate of dissolution of calcium carbonate at depth was high. The fact that calcium carbonate tends to be constant throughout the upper part of cores from lesser depths in the same general area as the type 1 favors the second hypothesis. The stratification of type 3, which as yet has been found only below and slightly north of the Equatorial divergence, is probably due to the increased rate of upwelling and consequently higher plankton production during glacial time (Arrhenius, 1952, p. 15–23).

RATES OF DEPOSITION AND THICKNESS

In most topographic lows of the pelagic regions, deposition seems to have been relatively continuous throughout the thickness of sediments sampled by 10-m cores. During the late Quaternary there appears also to have been a considerable areal uniformity in the rate of deposition of the clay components of the sediments, at least in the equatorial eupelagic area (Arrhenius, 1952, p. 25–28). However, large regional variations in the rates of accumulation and dissolution of calcareous and siliceous plankton shells resulted in considerable regional variation in the average rate of deposition of the sediments as a whole, in addition to the great local variations due to irregular bottom topography.

Near the Equator in the eupelagic area, where organic productivity is relatively high, the average rate of deposition for the last 14,000 years amounts to 2.0 g of dry, salt-free sediment per cm^2 in 1000 years, corresponding to approximately 3.2 cm of wet, uncompacted calcareous ooze. This estimate is based on radiocarbon data (Arrhenius, Kjellberg, and Libby, 1951, p. 222–229) from a core collected by the Swedish Deep Sea Expedition. The highest estimated rate in the same core amounts to 4.1 g/cm^{-2} in 1000 years, or 7.0 cm wet sediment per 1000 years. This estimate is based on the assumption of a constant rate of accumulation of nonbiogenous matter equal to that found in the postglacial stratum—*i.e.*, 0.073 g/cm^{-2} in 1000 years, or approximately 0.26 cm of wet clay. If this rate approaches an average for the pelagic clays, the total thickness of Tertiary clay deposits would approximate between 100 and 200 meters.

Raitt's seismic-refraction and reflection measurements (1953) indicate a thickness of about 200 meters of relatively unconsolidated sediment in the clay areas and about 400 meters beneath the equatorial calcareous belt. It is an unsettled question whether the lower boundary of this sediment is formed by consolidated sedimentary rocks or lava flows and intrusions. The former alternative appears improbable, as much thicker layers of unconsolidated sediments are indicated by the seismic-refraction measurements in certain relatively small areas. The presence of sedimentary rocks with a high sound velocity beneath a few hundred meters of unconsolidated sediments would thus require the assumption of a great discontinuity in the sedimentation process.

It is perhaps significant that the estimated average thickness from the seismic measurements and the approximate rates of accumulation seem to carry us back only to the Cretaceous, and that pre-Cretaceous strata as yet are unknown within the Pacific basin.

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Hybridization between Fish Species in Nature

CARL L. HUBBS

THE Jordan school of ichthyology, in which I was nurtured, held steadfastly to the view that the lines between fish species are almost never crossed. This mistaken idea was perhaps in part a holdover of the pre-Darwinian concept of the immutability of species, but was, more pointedly, a reaction against the tendency of some European ichthyologists to explain as hybrids specimens that proved difficult to identify. This view that there is little or no natural hybridization between fish species may be further attributed to the circumstance that systematic ichthyology in America from about 1890 to 1920 was still essentially in the exploratory and species-naming stage, and dealt chiefly with marine fishes, which, as I shall point out, hybridize much less often than do freshwater fishes.

Early in my ichthyological career I encountered evidence that fish species do cross in nature, at times in considerable frequency. The analysis of such hybridization has ever since engaged my attention, in so far as other activities would allow. This report lays particular emphasis on the researches that I have conducted during the past thirty-five years, largely with the collaboration of my wife and of several students and colleagues, to all of whom I pay tribute. They might all appear as co-authors of this report. The studies continue.

During the first ten years of my intensive studies of the freshwater fishes of North America, from 1919 to 1929, I gathered strong circumstantial indications that the species lines are rather often crossed in nature, and during the following fifteen years, from 1929 to 1944, I was able, with the constant aid of Mrs. Hubbs, to confirm these indications, not only by the accumulation of much more circumstantial evidence, in part subjected to critical statistical analysis, but also by breeding experiments in the aquarium of the Division of Fishes of the then new Museum of Zoology at the University of Michigan.

Sunfish Hybrids

The first main project in this aquarium was the experimental verification of extensive hybridization between the well-known species of sunfish. I had already concluded, on the basis of circumstantial evidence, that certain supposed species had been based on interspecific crosses. The commonest of these, known as *Lepomis euryorus*, I had treated as a natural hybrid between the green sunfish and the pumpkinseed. By placing a male of the one species with a female of the other we soon were elated to observe the characteristic nuptial gyration of sunfishes, followed by the laying of eggs, some of which hatched. And from the eggs that hatched we developed a considerable number of the miscegenates into large adults. The characters matched those of the supposed species *euryorus* and were intermediate between those of the parental species. Similarly, we produced fine adults of the hybrid between the green sunfish and the bluegill. This hybrid cross, also with intermediate characters, had been passing under the name of *Lepomis ischyrus*. Other combinations were effected. Most of the interbreeding was quite voluntary; some was induced by pituitary injections.

From our studies of sunfish hybrids we learned many of the basic facts regarding the interspecific hybridization of these fishes. As already mentioned, the hybrids are intermediate in taxonomic characters between the parental species. They differ from either parental type, however, in several respects, all attributable to the still poorly understood phenomenon of heterosis, or hybrid vigor. That they grow faster than either parental species was shown by the analyses of size frequencies at determined ages in nature and by measurements of growth in aquarium and pond. The hybrids dominate in the social hierarchy (known in fishes as the nip order). When a mixed group is fed, the hybrids, larger and more vigorous than the pure species, take the food first. In general activity, as in holding fins erect (an indication of vigor), and in the depth, brightness, and intensity of color, the hybrids excel. The great majority of the hybrids in nature as well as in captivity are males. The hybrid males construct, fan, and guard their gravel nests with unusual vigor over a prolonged period, but to no avail, for they are sterile. Sections of the testes of hybrids, whether bred in tanks or caught in nature, show marked abnormalities. In the hybrids the tubules of the testis are often vacuolated and the spermatozoa, when produced, vary greatly in size. When stripped from the hybrids some of the spermatozoa are relatively so immense that the beating of the tails merely rolls them along. The abnormal spermatogenesis of the natural hybrids confirms their identification as hybrids and helps to explain their infertility.

The frequency of hybridization in nature between sunfish species seems to be determined by several ecological factors. There is a relatively high incidence of hybridization in ponds largely filled with vegetation and with very limited gravel areas, where the spawning fish are unduly crowded. Great scarcity of one species coupled with the abundance of another often leads to hybridization: the individuals of the sparse species seem to have difficulty in finding their proper mates. The introduction of a species into a pond inhabited only by other species is also conducive to interbreeding. This is true even for species that elsewhere have come to live together with little or no crossing. In some ponds the observed incidence of hybridization rises to over 10 percent.

In one stream near Ann Arbor I found about 95 percent of the sunfish to be hybrids between the green sunfish and the pumpkinseed. This finding, made early in the study, baffled me at first. On a visit to the Northville Hatchery near Ann Arbor the superintendent complained that the sunfish he had taken in the stream to serve as breeders had not bred in the pond. He scooped out a net full of what I at once recognized as hybrids. How could sterile hybrids, almost all males, attain a 95 percent dominance? I wracked my brain for an answer, which finally took form. There must be, I hypothesized, a pond downstream inhabited by the parental species, which cross occasionally, and the hybrids because of their superior vigor counter the stream current to reach the vicinity of the hatchery. I called the superintendent and learned that there was indeed a pond five miles downstream. We then seined in the pond just what the "desperation hypothesis" called for—the parental species and a few hybrids!

Ordinarily the sunfish hybrids are definitely intermediate and do not grade into either parental type. In three places, however, it was found that the characters of the especially abundant hybrids graded into those of each parental species. At each place the hybrids were further exceptional in that they were not predominantly males. At these three isolated spots, the genes were probably being exchanged—a point of considerable speciational significance.

The Case of the "Amazon Molly"

While we were still engaged in the experimental confirmation of interspecific hybridization in the sunfishes, fishes collected in northeastern Mexico by Drs.

yron Gordon and Edwin P. Creaser
osed a problem that cried for experi-
ental attack. *Mollienisia formosa*, a spe-
es of the viviparous topminnow family
oeciliidae, was brought back in only one
ex: all of the many specimens were
emale. Since this nominal species is in-
ermediate between the sailfin molly
Mollienisia latipinna) and *Mollienisia*
henops, hybridization was suspected.
e secured live material of all three types
nd in 1932 inaugurated a twelve-year
rogram of intensive breeding experi-
ents with these three species, and many
hers.

We proceeded at once to test the repro-
uctive behavior of the species of which
nly females had been collected. We
romptly mated some of these females,
hich we termed "Amazon mollies," with
e two suspected parental types. One
these, *Mollienisia latipinna*, has a longer
orsal fin than *formosa*, originating far-
er forward and with more rays (13 to
5 instead of 10 to 12); and it has a deeper
nd more strongly striped body. *Mol-*
enisia sphenops, the other suspected
arental form, has in contrast a shorter
orsal fin than *formosa*, originating far-
er back and with fewer rays (usually 9
the subspecies used), and it has a slen-
erer body with the streaks poorly de-
eloped. We soon obtained broods of
oung, all of which, in confirmation of the
eemingly impossible hypothesis that I
as forced to erect, proved to be females
xactly like their mothers, without any
ace of the distinctive paternal charac-
ers! Crossing *latipinna* and *sphenops*
eciprocally, we obtained hybrids almost
xactly like the all-female *formosa*, yet
ese laboratory-bred hybrids were bisex-
al, and produced intermediate offspring
n backcrosses. In our preliminary note
Science (Hubbs and Hubbs, 1932*b*) we
oncluded:

> The conditions demonstrated by this study,
> far as we know novel in the biology of the
> ertebrates are: (1) the abundant occurrence
> nature of a form of demonstrated hybrid
> rigin, having nearly all of the characteristics of a natural species; (2) the occurrence of a form as females only, over a wide portion of its range [in fact, we now know, over its entire range]; (3) the consistent and abundant production of wholly female and purely matroclinous young; (4) apparent parthenogenesis in nature.

We continued in our genetic test of the complete production of females and the totally matroclinous inheritance of *Mollienisia formosa*. Year after year and generation after generation, unto the twenty-first generation, our *Mollienisia formosa* females continued to produce all-female broods of fish, many hundreds in all, that were replicas of their mothers, although we had mated the mothers with all the available species of *Mollienisia* and with various simple and multiple hybrids between the species of this genus. We mated them with the black mutant of *Mollienisia*, that always throws black-blotched young when crossed with normally colored specimens of *Mollienisia* of the same or other species. We also had broods from matings of *Mollienisia formosa* with species of the related genus *Limia*, though such broods are not often produced. Twice we obtained two young by mating a *Mollienisia formosa* with a male of the mosquitofish, *Gambusia affinis*, belonging to a distinct subfamily. This amazing result, which we could hardly believe, suspecting an experimental error, led us to repeat trial matings of this heterogeneous combination. After several failures we planned and executed a forced mating. We injected a *Gambusia* male and an Amazon molly with pituitary extract to induce rapid and simultaneous maturity. We then injected some sperm stripped from the *Gambusia* into the tiny oviduct of the molly. In due term she gave birth to twelve healthy young, which all grew up into adult females—again just like the mother, with no trace of *Gambusia* characters. But the best characters in these fishes lie in the gonopodium, which is the anal fin of the male highly modified to serve as the intromittent organ. Being females, the offspring of the outcrossing showed no male characters—until we bathed some of them in the dilution of testosterone that we had found to be effective and thus forced them to develop the secondary male characters. The gonopodium that developed, normally, showed no trace of *Gambusia* characters, but was strictly that of a *Mollienisia.* Furthermore, the colors of the nuptial male of *Mollienisia* became evident.

Always the result was the same—all female young, fully typical of *Mollienisia formosa* in every detail of character, not only in the first generation, but also in subsequent backcrosses and outcrossings. Thus the male used may have had 6, 8, 10, 13, or 17 dorsal rays, but the progeny, modally, had 11 like their mother. Since we have found no trace of such genetic behavior in systematic characters of any other fishes, in this or other groups, and since *formosa* is very fertile, giving birth to full complements of healthy young that often all develop to maturity, we consider the genetic evidence as next to conclusive, that *formosa* transmits to all its offspring only its own maternal chromatin.

Mollienisia formosa seems to have arisen as a hybrid, but now has almost all the characteristics of a species. It is completely differentiated from its supposed parental species *latipinna* and *sphenops*, and certainly breeds true, much truer in all probability than most species. It justifies systematic consideration on ecological and historical grounds, which in this case as in general I regard as being quite as significant as the genetic potential: it has increased and spread, for it now occupies a considerable and definite range, including areas where only one of the parental species exists or has likely ever existed. In some places it outnumbers the parental species. The circumstances that its fecundity is high and that 100 percent of its population instead of little more than 50 percent are female breeders would seem to give it a definite selective advantage within the range of the genus, since it mates freely with the males of all species of *Mollienisia* and since the males of poeciliid fishes promiscuously mate with many females. We think it best to treat the Amazon molly as a species, presumably of hybrid origin. This is a special but particularly interesting and significant crossing of the species line.

Intermediacy of Hybrids

In all our work with hybrid fishes in this or any other family, the only taxonomic character that we have been able to attribute to the action of a single gene is the dorsal and anal ray numbers in the subspecies of the mosquitofish, *Gambusia affinis*, (Hubbs and Walker, ms.). The Atlantic Coast form, *G. a. holbrooki*, has 7 dorsal and 10 anal rays, the Mississippi Valley form, *G. a. affinis*, one fewer in each fin (6 dorsal and 9 anal). Intergrades, obviously produced through hybridization near the Gulf of Mexico in Mississippi and Alabama, have either 6 or 7 dorsal rays and either 9 or 10 anal rays. The sum of the ray counts is therefore 17 in the Atlantic Coast form, 15 in the Mississippi Valley form, and 15, 16, or 17 in the intergrades. The intergradation though narrow in area is gradual. First-generation hybrids have 7 dorsal and 10 anal rays, showing that the Atlantic Coast type is completely dominant in this regard. In the F_2 generation the condition shown by the intergrades is at once attained, for the dorsal rays are either 6 or 7, the anal rays either 9 or 10. Other characters, however, such as those of the gonopodium and of the sensory pores on the head, remain intermediate and give evidence of being due, like nearly all taxonomic characters, to multiple genes.

It has proved to be an almost universally valid rule that natural interspecific hybrids are intermediate between their parental species in all characters in which those species differ, whether they be external or internal, of shape, color, form, structure, or numbers of parts (vertebrae, gillrakers, fin rays, teeth)—except for some features that reflect hybrid vigor.

This intermediacy has been most extensively analyzed for the numerous hybrids we have described (Hubbs, Hubbs, and Johnson, 1943) in the family of suckers, Catostomidae, from many streams in the western states. Intermediacy is seen in such external characters as the coloration, the general body form, the size of the head, the length and protrusion of the snout, the size of the scales. The lips are definitely transitional in structure. When statistically analyzed the proportions and counts of the hybrids are seen to be not only definitely intermediate, but also of the same order of variability as shown by the parental species—strong evidence that the hybrids are of the sterile F_1 generation. The intermediacy may involve the type of relative growth. Internal characters, such as those of the skeleton, may also be transitional. When the values for the hybrids are computed as an index, on a percentage scale grading from the value for one parent, set at 0, to the value for the other, set at 100, the indices form a frequency distribution with the mode very close to 50, which represents ideal interjacency.

The most extensive data that we have analyzed for any one hybrid combination pertain to mass hybridization and species replacement in the Mojave River system. In our published study (Hubbs and Miller, 1942) we reported on 3350 individuals of the species *Gila orcutti*, that we now feel sure was introduced, on 1812 of the native chub, *Siphateles mohavensis*, and on 442 hybrids, constituting 7.9 percent of the entire random sample (or 9 percent if we exclude the fish collected from one spring, into which the introduced species has no access). The hybrid proved on analysis to be intermediate in nearly all characters of color, form, and number of parts. The variable intermediacy extends to such fine characters as are exhibited by the scales. Particularly significant is the intermediacy of the hybrids, with very little overlap on the frequency distribution of either parental species, in the number of gillrakers. The native chub, though confined in Recent times to trickling streams, has very numerous rakers, which were obviously adapted for the straining of plankton in the large lakes that occupied the depressions of the Mojave Desert in Pluvial times. The minnow introduced (as bait) from the coastal streams of southern California has very few rakers, since its diet is essentially the bottom invertebrates, for the consumption of which it has no need for a fine straining apparatus. Data from successive years showed a marked increase in the relative numbers of the introduced species, which seem much better adapted than the relict lake chub to the present-day desert trickles. Collections made in 1953 indicate that the better-adapted introduced species has now almost completely replaced the doomed native form. Hybridization has doubtless co-acted with competition in this rapid replacement of a less well-adapted native species by a better-fitted introduced form.

Although it has long been recognized that interspecific hybridization is a common and important phenomenon in the Plant Kingdom, it has generally been held that in the Animal Kingdom species lines are only rarely, sporadically, and insignificantly crossed. In order to appraise the significance of interspecific hybridization among fishes, we will need to consider for different groups and in different habitats, the extent of such crossing, in terms of the number or proportion of species that cross and, in given combinations, in terms of the number or proportion of hybrid individuals. We also need data on the fertility of the hybrids when intermated, when backcrossed to each of the parental species, and when outcrossed with still others. We also need to know the viability of the hybrids and their chances of survival under different conditions. Some of these numerical relations have been determined; other determinations await much more observational, statistical, and experimental evidence.

Marine Fishes

An extended search by us for natural hybrids, involving the careful examination of about one million specimens of freshwater fishes and about an equal multitude of marine species, has yielded, along with the results of research by others, some idea of the frequency of hybridization. Two conclusions stand out vividly, (1) that frequency of hybridization, like speciation in general, is to a large degree a function of the environment, and (2) that among marine fishes in general, as contrasted with northern freshwater fishes, hybrids are excessively rare.

The one group of marine fishes in which hybridization is both fairly common and well authenticated is the flatfishes. In Europe there have been discovered hybrids of one interspecific (and intergeneric) combination among the turbots and of four combinations among the right-eyed flounders. One combination, between flounder and plaice, is rather common and has been experimentally produced. Stocks of hybrids of this combination have been planted to test migrations and survivals. Two combinations in the Pleuronectidae have been identified from western North America, and we have analyzed in detail the rather common hybridization of two genera in Japan (Hubbs and Kuronuma, 1942). Hybridization among the flatfishes has been attributed to their life on very uniform sand and mud bottom and to promiscuous mass spawning. Years ago I discovered that two species of silversides (family Atherinidae) living on the sand bottom of the South Atlantic coast hybridize rather frequently, and this case has been analyzed by Gosline (1948).

With these exceptions, hybridization between marine species has been detected or definitely suspected to occur in only a few scattered combinations and with extreme rarity in these few combinations. This is true despite the fact that in cool and more especially in warm seas many closely related species live together. True, much of the study of marine fishes has been less extensive and less intensive than the researches that have led to the recognition of so much crossing of the species in fresh waters, but along the West Coast, from Alaska to Mexico, and to a considerable degree in Japan and on the Atlantic coast of North America, we have done systematic work comparable to that which we have done on the freshwater fishes of North America. The researches we are now undertaking on pelagic and bathypelagic fishes are disclosing no hybrids. Before we attempt an appraisal of this difference in the incidence of hybridization, let us briefly review the evidence on interspecific hybridization in different families of fishes in the fresh waters of North America.

Hybrids in Freshwater Fishes

Among the lampreys (Petromyzontidae) we have moderately conclusive evidence of occasional hybridization between two freshwater species of *Ichthyomyzon* (Hubbs and Trautman, 1937).

Among the trout we find occasional intergeneric hybrids in nature as well as in culture. Most of these are between the native brook trout and the introduced brown trout. In the West the cutthroat and rainbow trouts, both belonging to the genus *Salmo*, live side by side with little or no crossing in many coastal streams, but in the interior, where the cutthroat alone was native, the introduction of rainbows has repeatedly led to very extensive hybridization, and frequently to the elimination of the cutthroat, through a combination of hybridization and superior competition. The rainbow and golden trouts hybridize similarly. In the hatcheries many crosses have been produced between good species of chars, trouts, and salmons. Some of these produce fertile offspring, and by mating one hybrid with one of another cross, four species of the Pacific salmons have been combined in one individual (among the poeciliids we have thus combined as many as five species and twelve subspecies or races). One combination, between the brook trout and the lake trout, is being propagated in Canada with promise of use in fish management. The parental species were formerly classed as distinct genera, but in the current lumping spree both are put in *Salvelinus* —which action does not lessen the difference between the species.

Hybrids between the whitefish and the lake herring or cisco of the Great Lakes, of the related family Coregonidae, have been found in nature (rarely) and have been experimentally produced (Koelz, 1929). They also represented an intergeneric cross a few years ago, but only an interspecific cross now, owing to the revised generic delimitations—a subjective matter. I have interpreted other specimens as interspecific hybrids within the subgenus *Leucichthys*.

Attention has already been given to hybridization in the suckers (Catostomidae), with reference to the characters of the hybrids, but we need to indicate the frequency of hybridization and its relation to the phylogeny of the group. In our first and most comprehensive study (Hubbs, Hubbs, and Johnson, 1943), we identified from the Western states 182 interspecific hybrids representing nine interspecific and in part intergeneric combinations. The 182 hybrids were 11.5 percent as numerous as one parental species taken in the same collections and 7.2 percent as numerous as the other parental species. In terms of all specimens examined from the same river system, the hybrids were 1.8 percent as numerous as one parental species, 1.5 percent as many as the other. In some crosses the hybrid ratio was higher; in one intergeneric cross in the Columbia River system the ratios of hybrids to the two parental species were 15.1 and 21.6 percent for collections containing hybrids, and 6.4 and 4.2 percent for all specimens known from the entire river system. Owing to the mass collecting technique of modern times there has been little selection of hybrid specimens in the field. It seems safe to conclude now, as it was when we published the main paper, that among the suckers in all the lakes and streams of the Western states at least one in a hundred is an interspecific hybrid. Conditions conducive to hybridization include the association of a few individuals of one species with an abundance of another, and the introduction of one species into the natural range of another. When thus thrown together, types that avoid hybridizing, where they occur together naturally, will cross. Subsequent studies (Hubbs and Hubbs, 1947; Hubbs and Miller, 1953; and ms.) have confirmed and expanded the conclusions reached in the paper cited.

For the suckers, and for several other freshwater fish families of North America, charts (Figs. 1 to 8) have been prepared to show by white rectangles the combinations of which no species occur in the same region, and hence cannot be expected to hybridize in nature; by gray rectangles, those that do occur together, but are not yet known to include hybrids; and by black rectangles, the combinations that include, to the best of our knowledge or judgment, at least one interspecific hybrid. Each such entry may represent several different interspecific combinations; of each combination we may have studied many series of specimens, and the total number of specimens may run into dozens or even hundreds. The recognized subfamilies are separated by heavy lines and the tribes by medium-weight lines. The genera are in full capitals; the subgenera, bracketed together, in lower case. The sequence is intended to be phylogenetic (in so far as may be indicated by a single column), so that combinations among most closely related generic groups should cluster along the diagonal, along which lie the combinations within each of the charted units. Note that for the Catostomidae (Fig. 1) the known hybrids are confined to tribal limits. All of the many sucker hybrids already discussed belong in the one tribe Catostomini. The other hybrid suckers that have been observed are between two buffalofishes (subfamily Ictiobinae).

The largest number of hybrid combina-

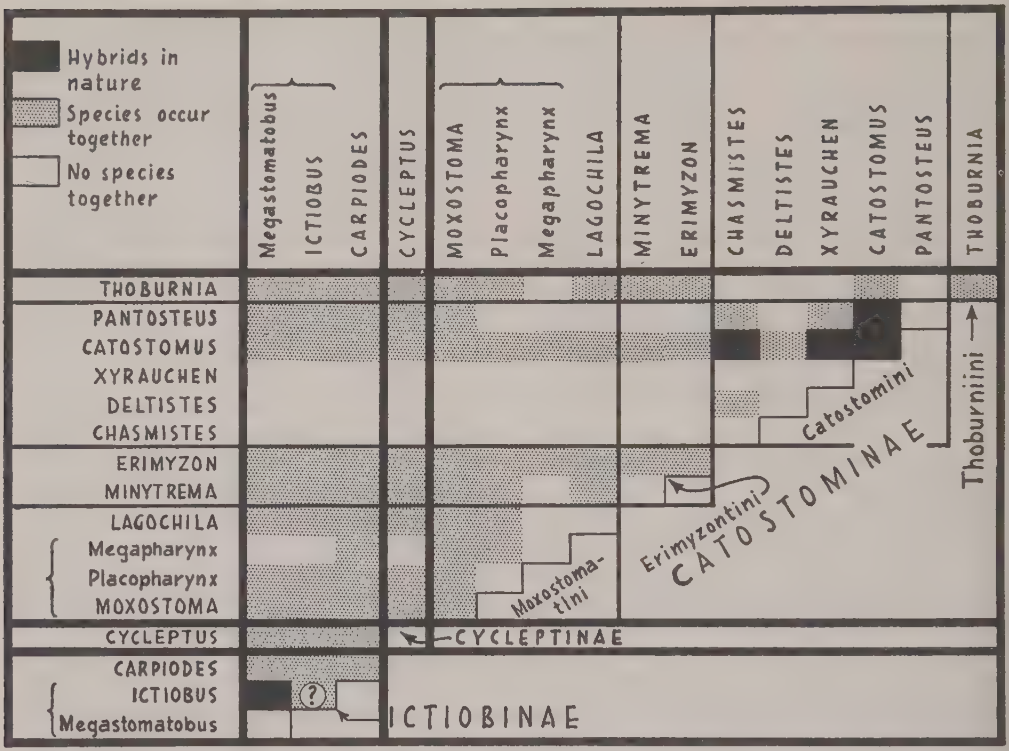
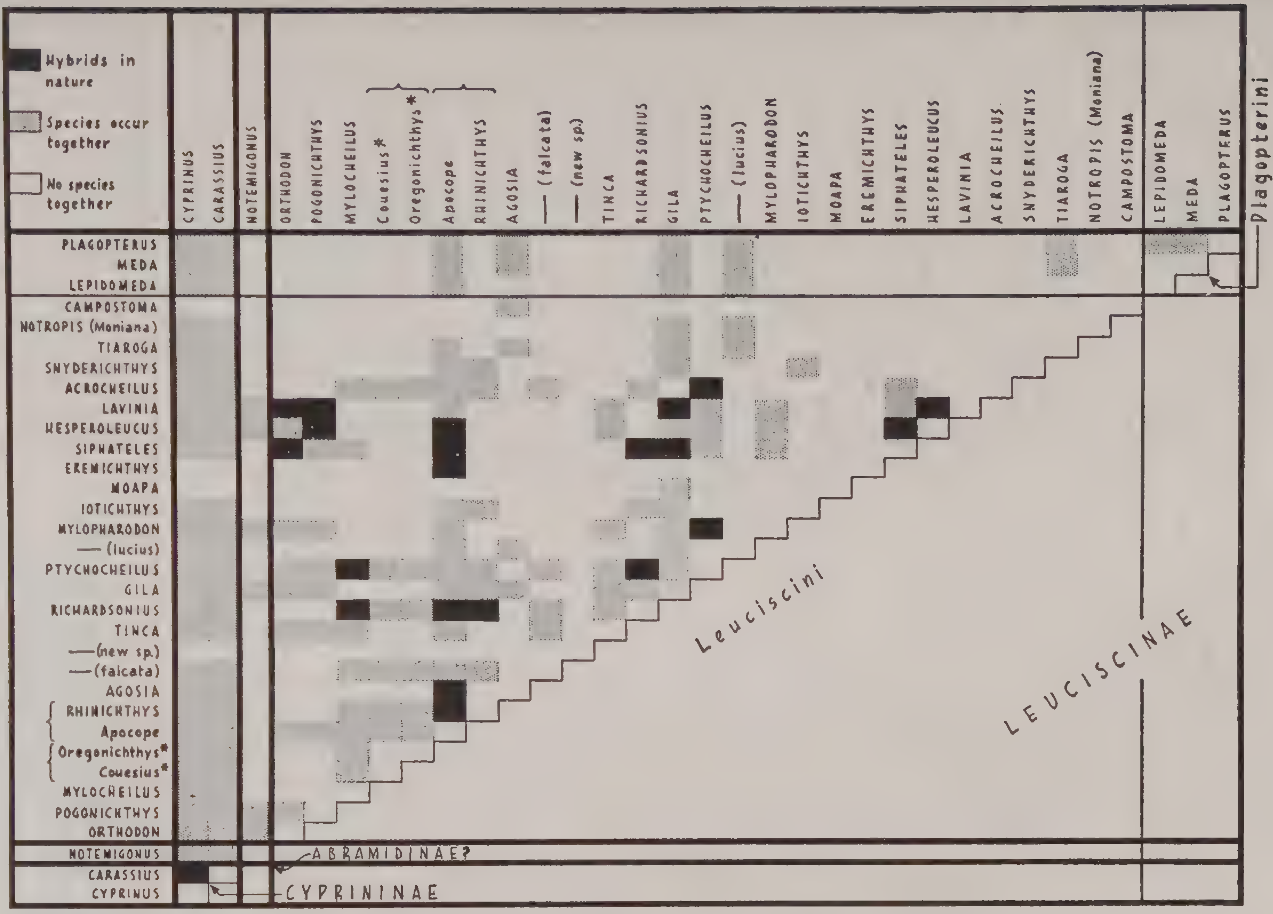

Hybrids in nature
Species occur together
No species together
Megastomatobus
ICTIOBUS
CARPIODES
CYCLEPTUS
MOXOSTOMA
Placopharynx
Megapharynx
LAGOCHILA
MINYTREMA
ERIMYZON
CHASMISTES
DELTISTES
XYRAUCHEN
CATOSTOMUS
PANTOSTEUS
THOBURNIA
THOBURNIA
PANTOSTEUS
CATOSTOMUS
XYRAUCHEN
DELTISTES
CHASMISTES
ERIMYZON
MINYTREMA
LAGOCHILA
Megapharynx
Placopharynx
MOXOSTOMA
CYCLEPTUS
CARPIODES
ICTIOBUS
Megastomatobus
?
Thoburniini
Catostomini
CATOSTOMINAE
Erimyzontini
Moxostomatini
CYCLEPTINAE
ICTIOBINAE

FIG. 1. Classification of North American Catostomidae, with indication of recognized hybrids between subgenera (printed in lower case) and genera.

tions occurs in the Cyprinidae, which is by far the most speciose family of North American freshwater fishes. The subgenera and genera of minnows are so numerous that we are forced to set up separate diagrams for the Pacific and Atlantic slopes. Taking the chart for the western slope (Fig. 2), we note first (at the lower left) hybridization between the carp and the goldfish in the subfamily Cyprininae. This cross has been produced in captivity and occurs very commonly in the East, especially about Lake Erie, where goldfish that escaped in a storm from a rearing pond got into Lake Erie, multiplied, and started interbreeding with the carp, previously established. The hybrids have become rather abundant locally. In one small creek in Ohio we found that the physiologically active hybrids had sorted themselves out, as sunfish hybrids sometimes do, so that, locally, they greatly outnumbered the parental species combined. In their native home, in eastern Asia, the two genera live together with little or no miscegenation, though they have been crossed there in captivity. Seemingly because of separation for a few decades or centuries, the two types have lost the art of avoiding the wasteful practice of producing sterile offspring (the uniformly intermediate characters of the hybrids indicate sterility). The carp-goldfish hybrids are uniformly intermediate, with about the same variation as each parental species. They are being reared for sale as bait, as they grow rapidly, are very hardy, and, being sterile, will not become established when bait is released.

The other hybrids among western cyprinid fishes involve crosses between rather diverse genera. In certain waters



*Subgenera of Hybopsis

FIG. 2. Classification of the Cyprinidae of the Pacific slope north of Mexico, with indication of recognized hybrids between subgenera (printed in lower case) and genera (omitting *Tinca*, an introduced genus not known to hybridize with other genera).

most of the genera hybridize with one another in different combinations, sometimes rather commonly so. In one rather isolated stretch of the San Juan River of the Salinas system the genera *Hesperoleucus* and *Lavinia*, like certain plant species, have crossed to produce a hybrid swarm, involving almost the entire population and, locally, breaking down completely the bars between the species. Because of the sharp differentiation of the Western freshwater fish faunas, a large proportion of the genera and subgenera do not cohabit. Of the 120 pairs that do occur together, 17 percent have already been found to produce hybrids in nature. Three more of the combinations produce hybrids on the Atlantic slope.

In the chart for the Atlantic drainage (Fig. 3) we have omitted the Cyprininae, containing the carp and the goldfish and their numerous hybrids, already discussed, and three other exotic genera that are not known to hybridize in any way. For some unknown reason, the golden shiner, *Notemigonus*, seems to be immune to crossing on either slope. In the East a much higher percentage of the generic groups live together and hybridization is scattered throughout the series of native fishes. Formerly these minnows were placed in several subfamilies, but I am now inclined to class them in a single subfamily, even in a single tribe (Leuciscini). The apparent freedom of crossing is one reason for this changed evaluation. The record would seem to indicate that the cyprinids did not populate America prior to the Miocene and that at most a few immigrants have through radiative adaptation erupted into the very rich Recent fauna. Hybridization has remained, or has become very widespread. The very highly aberrant genus *Campostoma*, with the intestine wound spirally around the gasbladder, crosses with seven other genera. The subgenus *Luxilus* of the very speciose genus *Notropis*, containing the common shiner *Notropis cornuta*, hybridizes with fourteen other subgenera and genera. Of the 608 pairs of subgenera and genera that live together, 68 (11 percent) have hybridized in nature, according to our best evidence. The interspecific combinations are more frequent than the subgeneric in number, of course, but not proportionwise. The chart of hybridization has grown with the years, until most of the major areas of possible hybrids have received at least one entry. It has been like filling in the periodic system of the elements.

Hybridization in the minnows has been attributed largely to the chance meeting of sperm and egg. As many as six or more species may be seen breeding violently on a single small gravel patch, commonly the nest of a large species. Very frequently *Notropis rubella* spawns in midwater a few inches above *Notropis cornuta*, which spawns on the bottom. The hybrids between these two species are perhaps the most commonly taken of any combination. The actual nuptial embrace of one species by another has not been observed, but is unnecessary to explain the frequent hybridization. Since the hybrids between *Notropis rubella* and *N. cornuta* appear to bridge the gap between the two species and have a normal sex ratio, it is assumed that they are at least partially fertile. The numerous hybrids between *Chrosomus eos* and *Chrosomus neogaeus* (formerly *Pfrille neogaea*) are invariably or almost invariably female.

Among the North American freshwater catfishes, the Ameiuridae, the few known hybrids are between species of *Ameiurus* and between species of *Schilbeodes* (Trautman, 1948; W. R. Taylor, ms.). A close connection between hybridization and classification is again indicated. In the South American catfish family Pimelodidae I have found a few hybrids between two species of *Rhamdia* in Guatemala.

In the pike family Esocidae (with one genus *Esox*) hybridization is rather common in nature and has been checked experimentally, but only the species of adjacent size seem to cross: the 10-inch

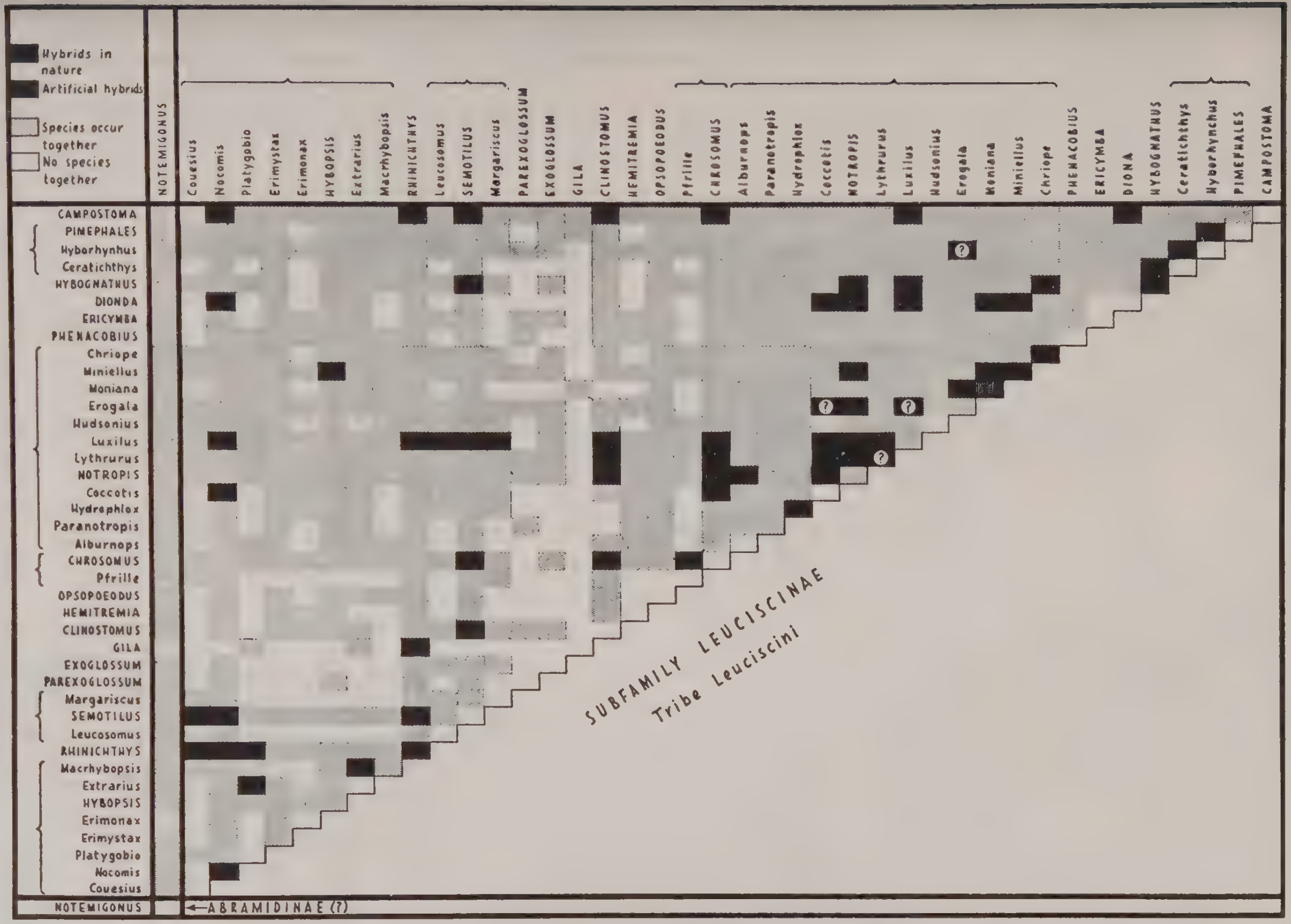


FIG. 3. Classification of the Cyprinidae of the Atlantic slope north of Mexico, with indication of recognized hybrids between subgenera (printed in lower case) and genera (omitting the Cyprininae, which are included on Fig. 2, and three genera, *Tinca*, *Scardinius*, and *Rhodeus*, that are not known to hybridize in North America).

bulldog pickerel (*americanus*) with the 18-inch chain pickerel (*niger*); the chain pickerel with the 3-foot northern pike (*lucius*); and the pike with the 5-foot muskellunge (*masquinongy*). The last-named cross has received some attention in fish culture (Eddy, 1944; Black and Williamson, 1947, with other citations).

Among the killifishes, or oviparous cyprinodonts (Fig. 4), a few of which range into brackish or even salt water, three interspecific combinations are known, all within the primitive tribe Fundulini (Hubbs, Walker, and Johnson, 1943). Hybridization in this group seems to be conditioned by cohabitation of a few individuals of one species with an abundance of the other.

Among the viviparous cyprinodonts two species of the Mexican family Goodeidae, regarded as generically distinct though closely related, have been found to hybridize rather commonly (Hubbs and Turner, 1939).

In the larger and more widespread, exclusively American family Poeciliidae very few natural hybrids are known, though members of this family have been more extensively hybridized than any other in home aquaria and in genetic laboratories. One reason seems to be that this group has a very wide range, from central United States to Argentina, so that many of the genera are of such limited range that they occur with few others, some with no other. Another reason is that copulation in this group follows complex nuptial performances, often characteristic of genera. In the large subfamily Gambusiinae (Fig. 5) very few hybrids have been identified, representing two subgeneric crosses in the mosquitofish

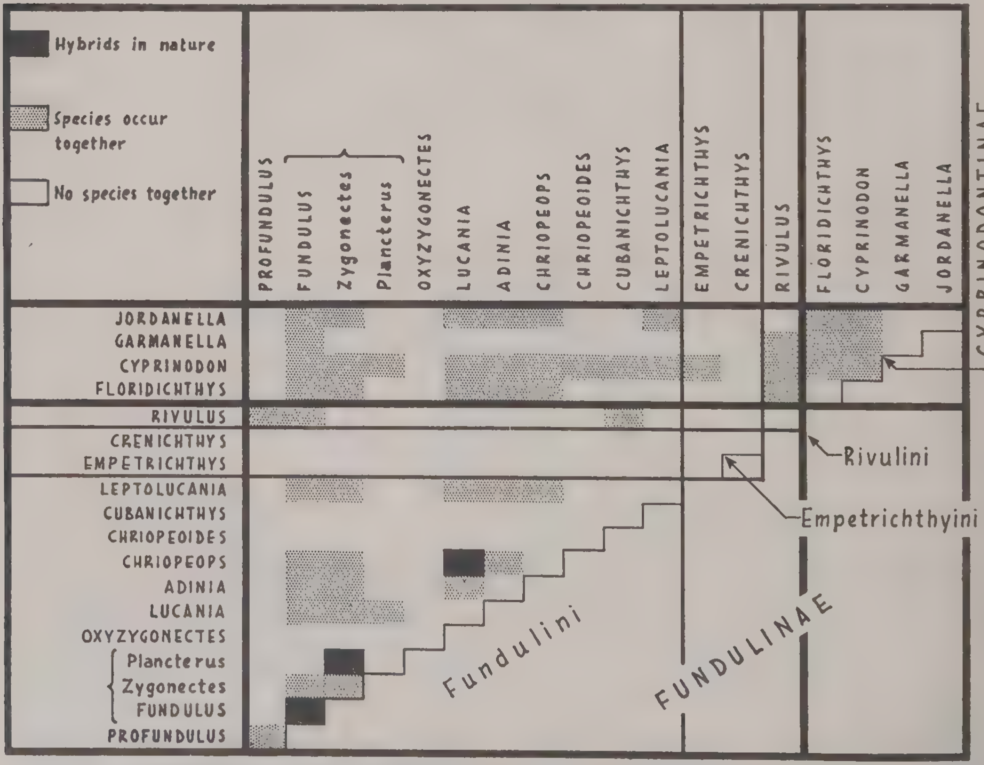

Hybrids in nature
Species occur together
No species together
PROFUNDULUS
FUNDULUS
Zygonectes
Plancterus
OXYZYGONECTES
LUCANIA
ADINIA
CHRIOPEOPS
CHRIOPEOIDES
CUBANICHTHYS
LEPTOLUCANIA
EMPETRICHTHYS
CRENICHTHYS
RIVULUS
FLORIDICHTHYS
CYPRINODON
GARMANELLA
JORDANELLA
CYPRINODONTINAE
JORDANELLA
GARMANELLA
CYPRINODON
FLORIDICHTHYS
RIVULUS
CRENICHTHYS
EMPETRICHTHYS
LEPTOLUCANIA
CUBANICHTHYS
CHRIOPEOIDES
CHRIOPEOPS
ADINIA
LUCANIA
OXYZYGONECTES
Plancterus
Zygonectes
FUNDULUS
PROFUNDULUS
Rivulini
Empetrichthyini
Fundulini
FUNDULINAE

FIG. 4. Classification of the Cyprinodontidae of North America, with indication of recognized hybrids between subgenera and genera.

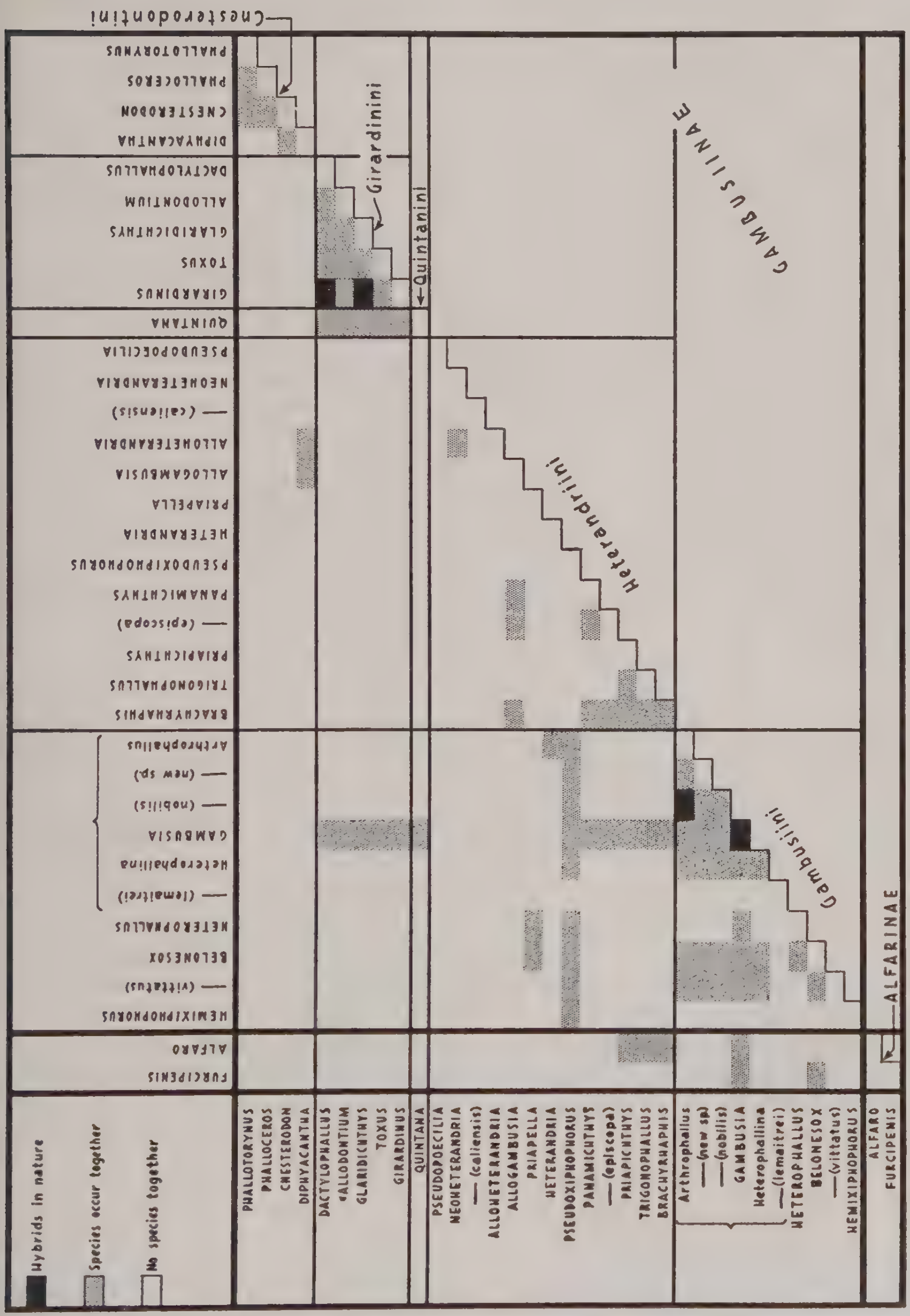

Hybrids in nature
Species occur together
No species together
PHALLOTORYNUS
PHALLOCEROS
CNESTERODON
DIPHYACANTHA
DACTYLOPHALLUS
ALLODONTIUM
GLARIDICHTHYS
TOXUS
GIRARDINUS
QUINTANA
PSEUDOPOECILIA
NEOHETERANDRIA
—(caliensis)
ALLOHETERANDRIA
ALLOGAMBUSIA
PRIAPELLA
HETERANDRIA
PSEUDOXIPHOPHORUS
PANAMICHTHYS
—(episcopa)
PRIAPICHTHYS
TRIGONOPHALLUS
BRACHYRHAPHIS
Arthrophallus
—(new sp)
—(nobilis)
GAMBUSIA
Heterophallina
—(lemaitrei)
HETEROPHALLUS
BELONESOX
—(vittatus)
HEMIXIPHOPHORUS
ALFARO
FURCIPENIS
Cnesterodontini
Girardinini
Quintanini
Heterandriini
Gambusiini
GAMBUSIINAE
ALFARINAE

Fig. 5. Classification of the subfamilies Alfarinae and Gambusiinae of the Poeciliidae, with indication of recognized hybrids between subgenera and genera.

genus *Gambusia* and two intergeneric combinations in the Cuban tribe Girardinini (Hubbs and Rivas, ms.).

In the subfamilies Poeciliopsinae and Poeciliinae, also, very few natural hybrids are known (Fig. 6). Dr. Robert Rush Miller, however, has found considerable hybridization between certain species of *Poeciliopsis.* In the tribe Xiphophorini no natural hybrid has yet been identified, though all species seem to be crossable in aquaria and most combinations have been effected. The very extensive genetic work by Gordon, Kosswig, and others has been done in this tribe, with crosses between the various species of swordtails and platies (all now classified in the genus *Xiphophorus*).

In the tribe Poeciliini we have found in nature a very few natural hybrids between species of *Mollienisia,* in Yucatan (Hubbs, 1936), Guatemala, and Hawaii (a different interspecific combination in each country). In Hawaii, where both genera were introduced, I have also found hybrids between the related genera *Limia* and *Mollienisia.* Crosses between *Lebistes* and *Mollienisia* have been made in home aquaria and have been verified by me. Various other crosses have often been claimed, as between *Lebistes* and *Xiphophorus,* but every such supposed intertribal cross that I have checked has proved to be referable to one or the other of the alleged parental species.

Probable hybrids of one combination have been reported in the freshwater Atherinidae (Jordan and Hubbs, 1919, p. 77).

In the perch family (Percidae) we find again a close correlation between hybridization and classification (Fig. 7). The

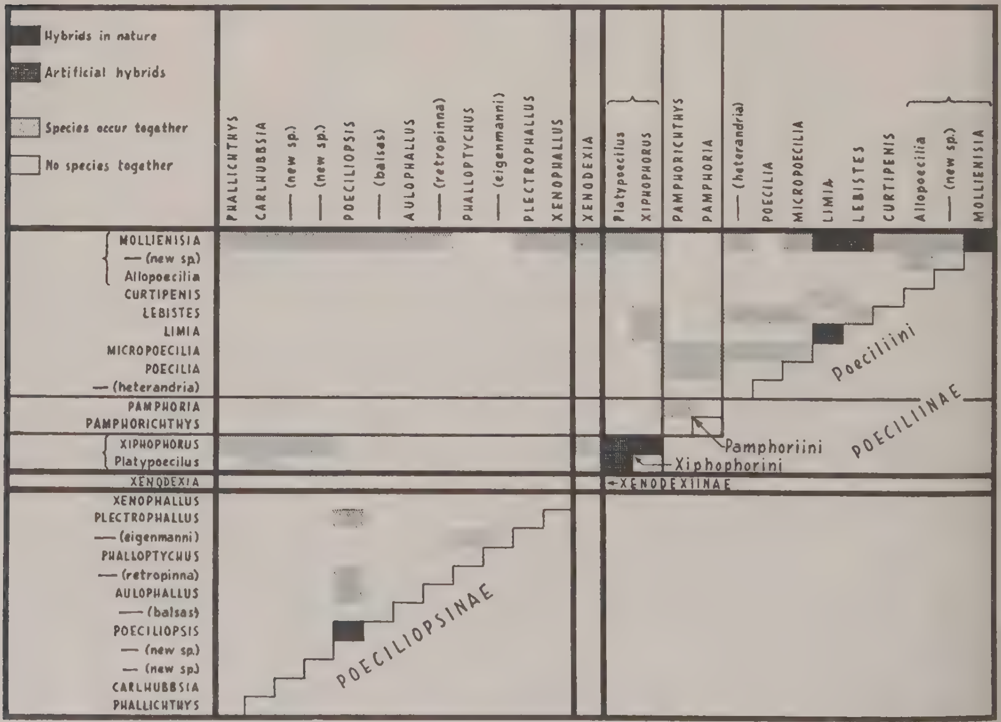


FIG. 6. Classification of the Poeciliidae of the subfamilies Poeciliopsinae, Xenodexiinae, and Poeciliinae, with indication of known experimental and natural hybrids between subgenera and genera.

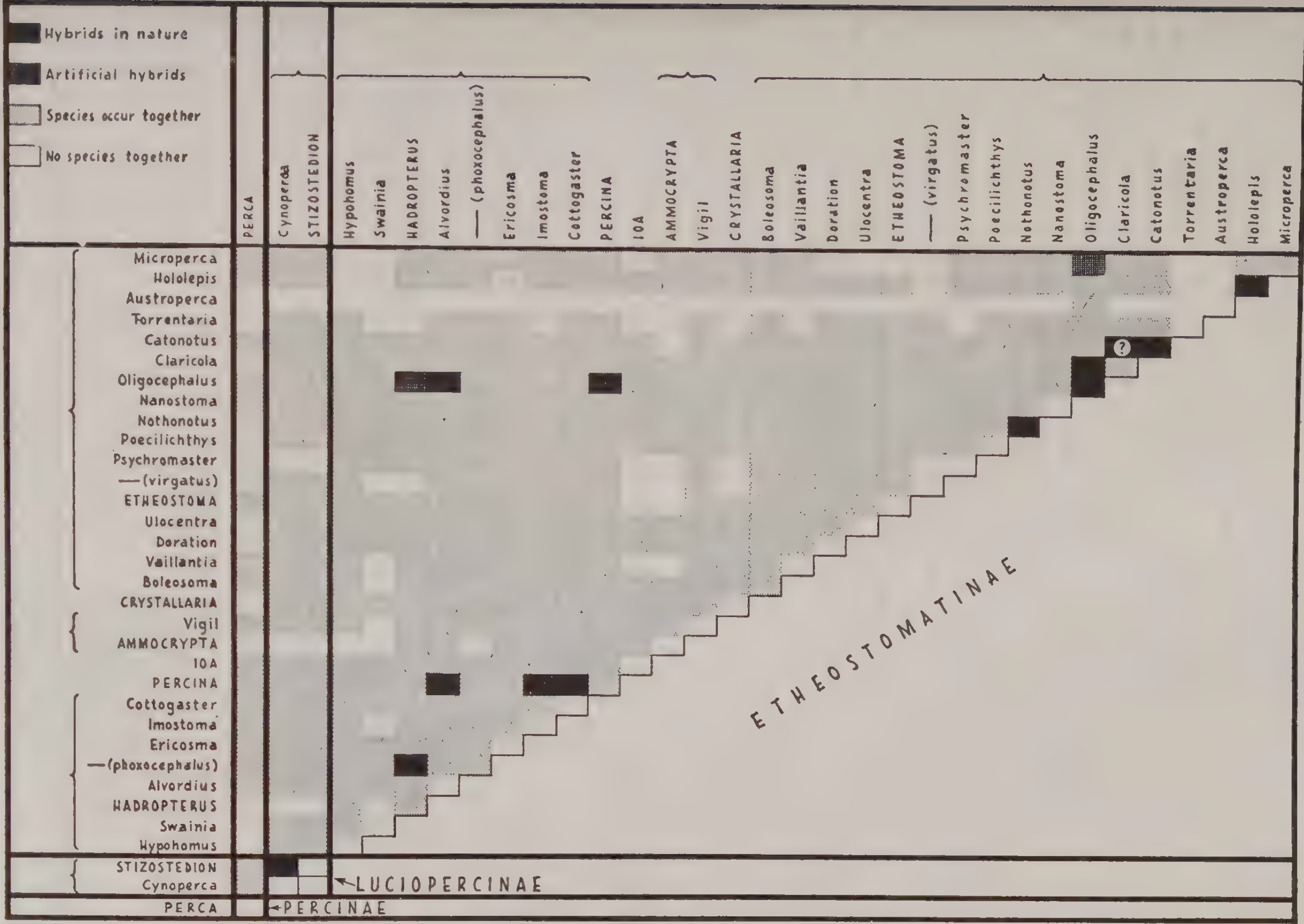


FIG. 7. Classification of the North American Percidae, with indication of known experimental and natural hybrids between subgenera and genera.

yellow perch, representing the Percinae, does not hybridize with any other fish. The two main species of the Luciopercinae hybridize occassionally, and the yellow and the blue walleye appear to cross so often that they are now treated as subspecies (the decision is in part arbitrary). No member of the Luciopercinae hybridizes, so far as is known, with any genus in either of the other subfamilies.

In the subfamily Etheostomatinae, the diminutive perches known as "darters," hybridization is moderately common but in nature is restricted largely to the less reduced and more primitive genera and subgenera. A few hybrids are known to occur between several species among the smaller and more brilliant, specialized darters, within a subgenus or between closely related subgenera. Among the thousands of specimens examined by me, only two represent natural crosses between the more primitive and the more specialized genera. Several laboratory crosses are being made by Clark Hubbs and by Allan Linder, with rather ready success among the highly specialized darters, but in general with poor success in crosses between the primitive and the specialized genera. Here again is evidence of a close correlation between hybridization and relationship. Crossing of the species line in this family as in the minnows may well result from the chance meeting of eggs and sperm when two species breed in close proximity, as they often do.

In the sunfish family Centrarchidae (Fig. 8), as well, hybridization is confined to the limits of single tribes. We have found several hybrids between species of blackbass, but only in the subgenus *Micropterus* (Hubbs and Bailey, 1940). Within the sunfish tribe Lepomini, comprising nine genera as recently classified but only two at present, by reason of lumping, 18 (about one-half) of the 38 possible subgeneric crossings have already

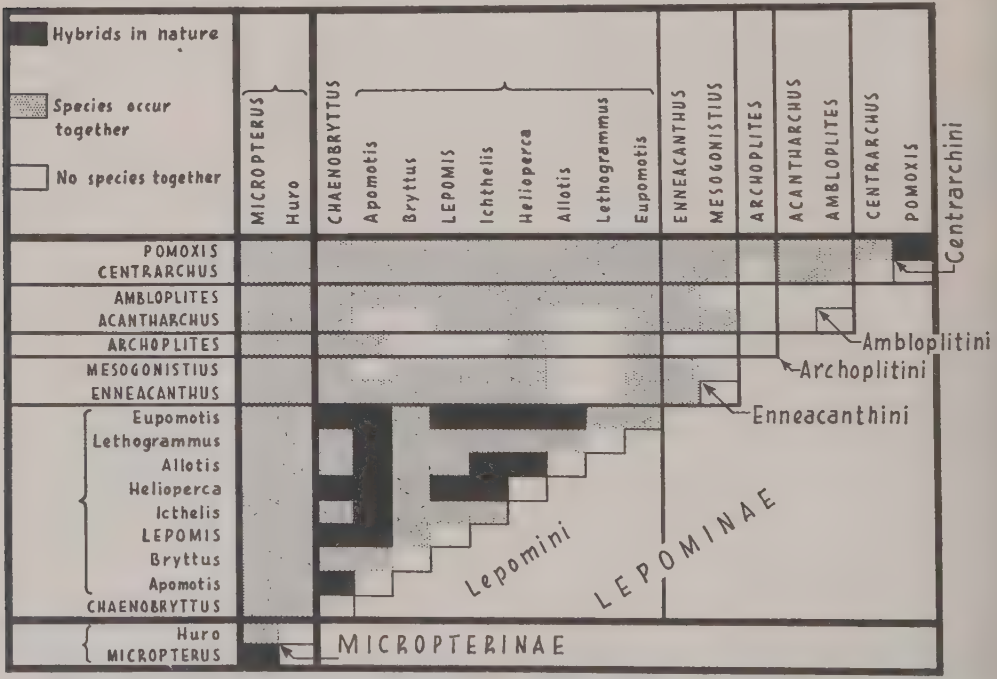

Hybrids in nature
Species occur together
No species together
MICROPTERUS
Huro
CHAENOBRYTTUS
Apomotis
Bryttus
LEPOMIS
Ichthelis
Helioperca
Allotis
Lethogrammus
Eupomotis
ENNEACANTHUS
MESOGONISTIUS
ARCHOPLITES
ACANTHARCHUS
AMBLOPLITES
CENTRARCHUS
POMOXIS
Centrarchini
POMOXIS
CENTRARCHUS
AMBLOPLITES
ACANTHARCHUS
ARCHOPLITES
MESOGONISTIUS
ENNEACANTHUS
Eupomotis
Lethogrammus
Allotis
Helioperca
Icthelis
LEPOMIS
Bryttus
Apomotis
CHAENOBRYTTUS
Huro
MICROPTERUS
Ambloplitini
Archoplitini
Enneacanthini
Lepomini
LEPOMINAE
MICROPTERINAE

FIG. 8. Classification of the Centrarchidae, with indication of recognized hybrids between subgenera and genera.

been realized. The main features of the abundant hybridization in this tribe have already been outlined. The other interspecific hybrids in the family are between the two species of *Pomoxis*, in another tribe.

The only other natural hybrid recognized in the fresh waters of North America is between two species of sculpins, of the genus *Cottus*, and this cross needs further study.

The frequent crossing of the species line in the freshwater fish fauna of eastern North America is duplicated in Europe in the minnow and trout families (where it would be expected). A few minnow hybrids have been reported from Asia and some of the Indian cyprinids have hybridized in aquaria. In Africa and South America, at least some interspecific hybridization can be predicted, though it has seldom been indicated. It is not at all improbable that hybrids in those continents have been studied and named as distinct species, just as the sunfish hybrids were in North America before they came under close scrutiny.

It would be of particular interest to determine whether and to what degree the species lines are crossed in the large lakes, especially the rift lakes of Africa, where radiative speciation has dramatically exploded, to produce rapidly, with very little geographic isolation, a great number of species. Under such conditions I would expect much crossing of the line between the recently differentiated species. Dr. Ethelwynn Trewavas of the British Museum has told me that she has reason to suspect that some of the variants and some of the nominal species encountered in the study of the extraordinarily numerous cichlid species of the African lakes may be interspecific hybrids. In critically examining Dr. Tchernavin's report on the multitudinous species of the cyprinodont genus *Orestias,* endemic in Lake Titicaca, Perú, I found evidence of some interspecific hybridization, and in treating the atherine genus *Chirostoma,* which has proliferated extensively in the lakes of the Río Lerma system of México, Jordan and Hubbs (1919, p. 31) discussed three probable interspecific hybrids of one combination.

The Role of Environmental Factors

Even if no further evidence of interspecific crossing among freshwater fishes should be discovered, the conclusion would stand out boldly that such hybridization is vastly more common in fresh waters than in the sea. This contrast cannot be attributed solely to a difference in the genetic potential of families respectively more or less confined to fresh and ocean waters, for the hybridization occurs in all of the larger families in North American fresh waters, including some families that have close relatives in the sea.

It is evident that the hybridization is conditioned by environmental factors. Some of these factors have already been indicated. Species that rarely or never hybridize in nature can often be crossed, sometimes very freely, in captivity. Merely placing a male of one species with a female of another in an aquarium may lead to crossing. Thousands of such matings between the swordtails and the platies have been consummated, yet not a single hybrid between the two has ever been taken in nature, despite the fact that they often occur together and have been very extensively collected and very critically studied. Species of *Mollienisia* that hybridize in nature with extreme infrequency cross very freely in aquaria, in some combinations with no decrease in fecundity in the first or even in the succeeding generations. Many combinations that seldom or never cross voluntarily, even in planned matings within the confines of an aquarium, prove their basic genetic compatibility when the breeders have been injected with hormones, or when artificial impregnation is practiced. The genetic potential often remains unrealized.

Similarly, where the spawning areas in

nature are greatly limited and the breeding fish are thus forced into close proximity, the incidence of hybridization is increased. Spawning in proximity may lead to the chance meeting of eggs and sperm, but may also lead to the mating of species that breed with complex pairing behavior. The cohabitation of a few individuals of one species with a multitude of a related species is another circumstance definitely conducive to crossing, especially when the scarcer species has been introduced. When ready to spawn, the species that is locally rare may outcross if the proper mates are not at hand. As in plants, hybridization is often a function of the intergradation of the habitat: species that are segregated in breeding by differential responses to any features of the physical, chemical, or organic environment tend to breed together where the environment is rendered intermediate, either through natural causes or through modifications by man. And species that normally breed at different seasons may cross where conditions are such as to cause an overlap in the breeding seasons.

In the light of these thoughts, how can we explain the high incidence of hybridization in the fresh waters of North America (and of Europe), in contrast to the infrequent breakdown of species lines in the sea? We attribute the frequent hybridization in the fresh waters in part to the greater opportunity for chance meeting of egg and sperm, but, more especially, to the ephemeral and changing nature of the environment. Lakes are temporary, often suddenly formed but all doomed to eventual extinction. Most lakes, of limited area and depth, are very transient. As they change in character and approach extinction the habitats are altered or destroyed. Streams also change in character in glaciated areas. In North America and Europe the almost catastrophic changes in climate through the Ice Age, modifying conditions and forcing dispersals, vastly decreased the long-term stability of the ecological niches, and it is in the regions affected sharply by Pleistocene stresses that hybridization has been encountered most often. In North American fresh waters, where hybridization has probably been most frequent, most of the existing fish fauna, furthermore, appears to date only from invasions during the Miocene, Pliocene, and Pleistocene, leaving no very great time for full adjustments. In addition, most freshwater fishes are so limited in possible movements that they cannot reach the full assortment of habitats that might otherwise be available.

In the sea, in contrast, and to a large degree perhaps in more nearly equatorial fresh waters, speciation has had a longer play. Local changes in both time and space may be rapid and profound, but the various ecological niches to which related species have become differentially adjusted remain available, if not in the immediate vicinity, at least within reach along the much freer highways of dispersal. The organic environment has apparently also remained more stable. Much greater opportunities have existed for the development and operation of the multitudinous fine adjustments involved in the location, with precise timing, of the proper breeding grounds and the proper mates.

Contrast in the regional incidence of hybridization may probably be drawn not only between fresh waters and the sea, but also between the temperate regions and the tropical. The environmental and particularly the organismal diversity of tropical regions seems to have been accompanied by very little interspecific crossing (though, as already noted, more critical and complete systematic studies may well disclose some hybridization in tropical fresh waters, and possibly even in tropical seas). The seeming lack of hybridization in the swarming reef fauna of the Indo-Pacific region is amazing. The fact that most of the few marine fish hybrids thus far recognized have come from temperate northern waters may be due not only to more complete studies there, but also to faunal disruptions induced to some extent in the littoral waters, as well as in fresh waters, by the vast shifts in Pleistocene climate. I venture to predict that the incidence of natural hybridization between species will show a clinal gradation from north temperate to tropical zones, as well as from fresh waters to the sea, with the highest frequency in Holarctic freshwater regions strongly affected by Pleistocene events and the lowest incidence in tropical marine waters. North temperate marine and tropical freshwater fishes may show an intermediate and rather low incidence. Similar relations may well hold for other groups of animals.

Selective advantage as well as conditions imposed more directly by the environment may help to explain not only the general avoidance of hybridization that I have attributed to environmental stability, but also the relatively frequent crossing of the species that seems to be a result of environmental instability. The general avoidance of crossing, where environmental stability permits, seems to be attributable not only to reduced fertility of the hybrids, but also to the selective advantage of the fine adjustments, between species and environmental niches, that can be attained only with relatively uniform genetic constitution. But where the environment is in a state of flux, increased premium may be inherent in the genetic variability that hybridization produces. Material is then needed for new adjustments to the rapidly changing environment. Under these conditions the advantages of genetic variability may outweigh the advantages of uniform constitution. Under more stable environments these opposing advantages may be reversed.

Frequency of hybridization appears to be inversely correlated with the number of species in given areas. It is certainly true in the Catostomidae (the suckers) and I believe also in the Cyprinidae (the minnows) that hybridization is more frequent in the fresh waters of western North America than in the more speciose waters of eastern North America. In the abounding fauna of the tropics many more species come in contact with one another, yet hybridization seems least common. One reason may be that the diversity lies largely in the organismal environment, under which conditions species recognition and specialized reproductive responses and behavior are presumably enhanced (the highly diverse species-specific coloration of tropical reef fishes comes to mind in this connection).

The absence or scarcity of hybridization where species are most numerous is one of several lines of evidence that belittle interspecific hybridization as an important factor in the speciation of fishes. The frequent if not usual sterility or partial sterility of the hybrids is another of the lines of evidence. There is a considerable body of circumstantial evidence, however, to indicate that in at least some groups of fishes in certain regions the crossing of the species line has been a factor of some significance in speciation, particularly in the way of introgressive hybridization.

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THE JOURNAL OF GEOLOGY
Vol. 63, No. 2, March 1955
PRINTED IN U.S.A.

CUSPATE SPITS OF ST. LAWRENCE ISLAND, ALASKA[1]

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ABSTRACT

Field and laboratory studies of large triangular projections in the lagoons of St. Lawrence Island in the Bering Sea indicate that these deposits were built by longshore drift of beach sand and were modified by currents in the lagoons. The term "cuspate spit" is suggested to designate such features. Possible origins include (1) deposition by opposing eddy currents, (2) deposition within wave shadows, (3) longshore drift, building a series of recurved points on a spit with later modification by waves, (4) repeated breaching of the lagoon barrier beach, with deposition of sediment washed through the opening, and (5) development by currents deflected or modified by sediment masses washed over the barrier beach during storms. Lagoon constrictions may be important in localizing the formation of these deposits.

INTRODUCTION

During the summer of 1949, while serving as a geologist of the U.S. Geological Survey, the writer had the opportunity to study shore features and collect sand and gravel samples from the beaches of St. Lawrence Island, Alaska. St. Lawrence Island lies athwart the southern end of the Bering Strait, 3° south of the Arctic Circle (fig. 1, inset). A large part of the island is tundra lowland, dotted with hundreds of small lakes and underlain mostly by sedimentary rocks. Intruded into these rocks are granitic masses, which form mountain groups or isolated peaks rising abruptly from the tundra. Such granitic mountains furnish most of the sand and gravel of shore deposits on the south side of the island. The north-central portion of the island is blanketed by Tertiary and Recent(?) volcanic rocks.

In the beach studies special attention was given the unusual triangular or cuspate deposits jutting from the barrier beaches and from the mainland into the protected lagoons on the south side of the island (fig. 1). So far as is known, the present study represents the first detailed examination of these shore-line features, although deposits similar in form or in physiographic setting have been recognized for many years. G. K. Gilbert (1885, p. 98) described and figured similar structures from the old shores of Lake Bonneville. Gulliver's "tidal cusp" (1896, p. 411–417), particularly in its lagoon-marsh stage, resembles some of the St. Lawrence Island deposits in form and setting. Following a suggestion by Shepard (1952, p. 1911), the term "cuspate spit" is used to denote this feature found within enclosed or semi-enclosed bodies of water, such as lagoons, in place of the terms "V-bar" and "V-terrace" of Gilbert or "tidal cusp" of Gulliver. The proposed term does not relate this shore form with any particular process of development such as the tides, but it does suggest its cuspate or V outline in plan and its protrusion above the water surface. It also avoids confusion with "beach cusps," which are more uniform in size and spacing and much smaller than these deposits.

Nearly twenty cuspate spits, from 350 to 3,200 feet in base-to-apex length, were observed. One especially symmetrical pair was selected for detailed study (pl. 1). Dimensions of the larger spit were measured with a transit. Surface samples of the sediments were taken at 250-foot intervals along the water line on both limbs of this spit and the adjacent barrier beach (fig. 2, inset). Two traverses were run across the spit to determine sediment variation across the limbs and bordering slopes and water depth in the shallow pool between the limbs. The velocity and direction of the wind and characteristics of waves and local currents within the lagoon were noted during the two days spent sampling the spit.

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[1] Publication authorized by the director, U.S. Geological Survey. Manuscript received March 16, 1954.

[2] Contributions from the Scripps Institution of Oceanography, New Series, No. 760.

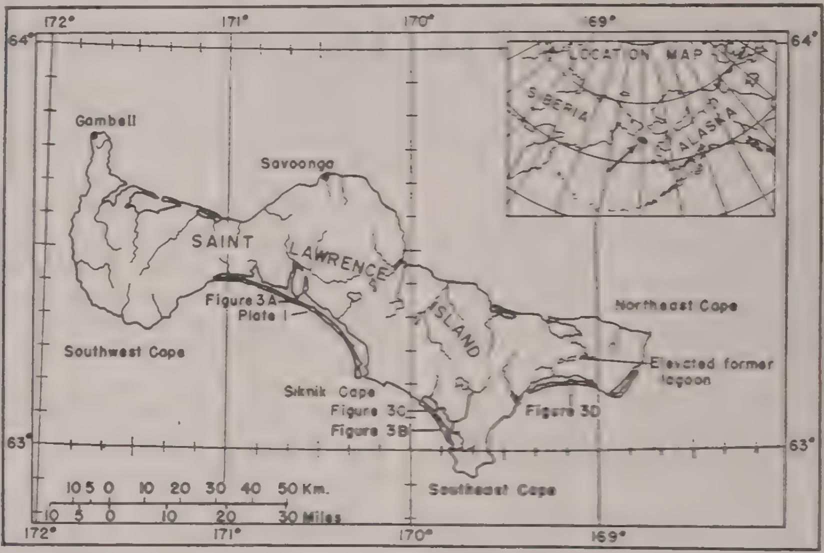
172°
171°
170°
169°
64°
63°
LOCATION MAP
SIBERIA
ALASKA
Gambell
Savoonga
SAINT LAWRENCE ISLAND
Figure 3A
Plate I
Southwest Cape
Northeast Cape
Elevated former lagoon
Siknik Cape
Figure 3C
Figure 3B
Figure 3D
Southeast Cape
10 5 0 10 20 30 40 50 Km.
10 5 0 10 20 30 Miles

FIG. 1.—Index map showing cuspate spit localities

TYPE LOCALITY

The cuspate spit sampled lies on the lagoon side of a barrier beach extending 29 miles along the south-central coast line of St. Lawrence Island (fig. 1). In the vicinity of this cuspate spit the lagoon is 3,500 feet wide, but it widens to 5,000 feet within a mile in either direction. The lagoon is connected to the sea by an outlet 17 miles to the southeast. A former outlet, 5 miles nearer the type locality, was sealed off by wave action between 1932 and 1943. Formation of the cuspate spits antedated closing of this lagoon entrance, for Eskimos gave the spits local names many years ago. Probably the lagoon has been sealed off and reconnected to the ocean a number of times since the spits were formed. Observations indicated no change in the level of the water in the lagoon during the day. A maximum current of $\frac{1}{3}$ mile per hour to the southeast between the cuspate spits

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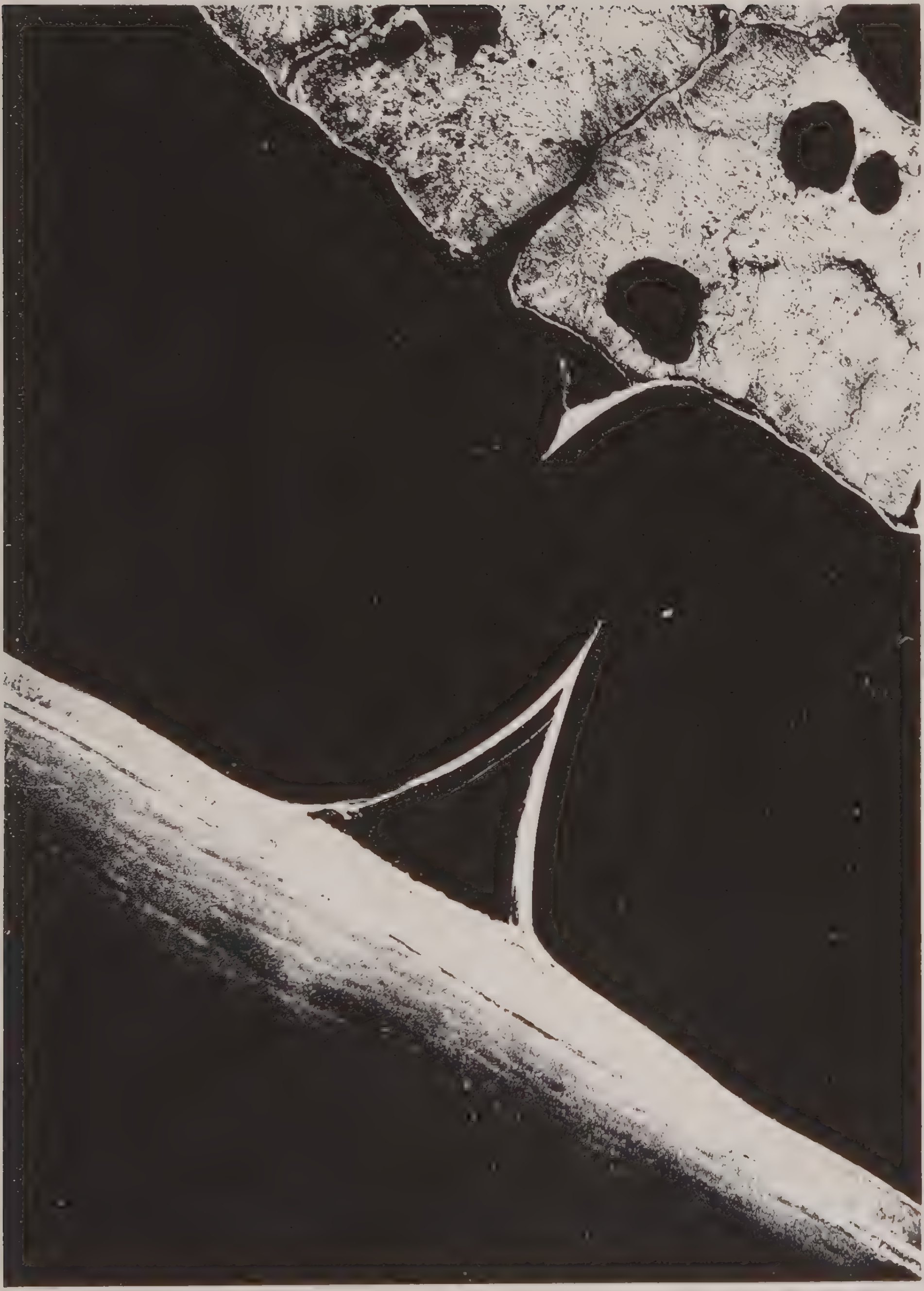
PLATE 1

Paired cuspate spits of which detailed study was made. (See figs. 1 and 2, inset.) U.S. Navy photograph.



Paired Cuspate Spits

was measured by drift of fluorescein dye. This current may in part represent flow toward the lagoon outlet from the large river that enters the lagoon several miles to the northwest. Weaker currents, possibly resulting from mild southwesterly winds, were observed to flow from base to apex along the outer edges of both limbs of the spit. In plan view the barrier beach shows a slight concavity along its inner edge a few hundred feet in each direction from the spit base (pl. 1), suggesting a possible source for the sediments comprising the spit.

The larger of the paired cuspate spits is 2,400 feet broad at the base and 2,500 feet from base to tip. The mainland spit is 900 feet broad and 950 feet from base to tip. The limbs of the major spit enclose a pool less than 18 inches deep. Its bottom is corrugated by small ridges nearly parallel to the present margins. These are probably "growth lines" and record previous positions of the limbs. One of these ridges, appearing as a white streak in plate 1, breaks the surface of the pool. The lagoon bottom drops off steeply from the edges of this spit, especially on the west side.

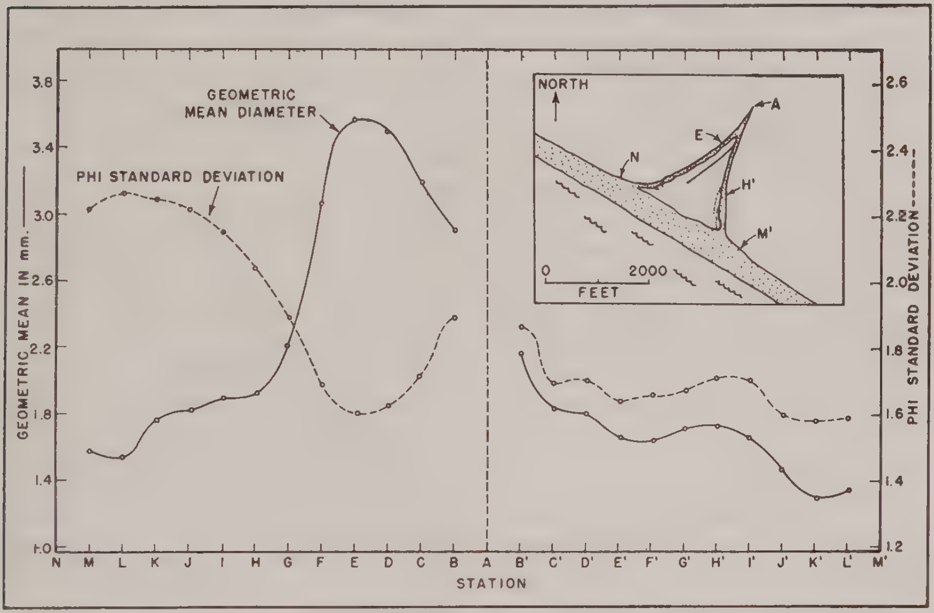


FIG. 2.—"Running plots" of sediment mean diameter and sorting. (For example, "Running mean diameter" for station

$$F = \frac{Dm_E + Dm_F + Dm_G}{3},$$

where Dm = mean diameter.)

Inasmuch as the cuspate deposits are composed of coarse sediments, 2- to 3-pound samples of the surface sands and gravels were secured at each station. Sieve analysis of these water-line samples yielded nearly log-normal frequency distribution curves, with a slight tendency to be skewed toward the fine-size classes. The northwestern limb of the spit shows a progressive increase in mean grain size from a sample point *N* on the barrier beach to a point *E*, five-sevenths of the distance to the apex (fig. 2). Sorting, as expressed by phi standard deviation, increases along this traverse, and the distribution curves lose their slight bimodal character. From point *E* to the spit apex, mean size decreases, and sorting becomes less perfect. The southeast limb displays a similar increase in grain size from base to apex, with a secondary maximum at a point *H′*. In general, the sediments of the southeast limb are finer than those of the northwest, and the sorting plot is more complex, with best sorting generally accompanying smaller mean grain size. "Running plots" of the size data have been made, in order to bring out significant trends along the limbs.

OTHER CUSPATE SPITS ON ST. LAWRENCE ISLAND

Although only one spit was sampled, others on the island were visited. Field observation and subsequent study of excellent aerial photographs lead to the following generalizations concerning these deposits. Cuspate spits are present both in open and in sealed lagoons. The paired spits described above are distinguished only by perfection of symmetry; the more usual spit is asymmetrical (fig. 3, *A*, *B*, *C*). Where currents are strong, that is, near lagoon openings or near the mouths of large rivers, the apex of the spit may trail out for thousands of feet. Small spits are commonly formed opposite small headlands or projections of the mainland into the lagoon, especially when such projections are bordered by rather deep indentations of the shore line (fig. 3, *A*).

Paired cuspate spits are by no means rare. In the pairs observed on St. Lawrence Island the spit based on the barrier beach was longer and better developed, possibly reflecting a more abundant source of sediment. Instead of joining at the apices, such paired spits are typically offset from each other, maintaining a channel between them. The channel between offset spits may become sealed by fusing of adjacent overlapping limbs. In this way the lagoon is segmented until a change in conditions causes breaching of the seal, as has happened on one present-day lagoon (fig. 3, *D*). The component spits of one such segmented lagoon can be distinguished clearly 2 miles inland on an emerged shore line formed when the sea stood several feet higher than at present (fig. 1).

In addition to cuspate spits, long, thin spits are being built parallel to the mainland shore or to the barrier beaches from shoals and islands within the lagoons. At intervals of half a mile or less, small cuspate spits join these linear spits to the mainland or barrier beach, resulting in a series of oval aligned lakes (fig. 3, *D*, lower portion).

SIMILAR FEATURES IN OTHER AREAS

Although the St. Lawrence Island cuspate spits are striking because of their regularity of outline, symmetry, and size, they are not unique. Similar features occur behind barrier islands and in lagoons along the Gulf Coast of the United States. Upper Pritchard Long Point is one of several sharp triangular structures behind Santa Rosa Island, near Pensacola, Florida. In the same general area symmetrical and recurved spits are developed in Little Lagoon, a recently sealed lagoon just east of the entrance to Mobile Bay. Comparison of modern

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charts with old surveys (U.S. Coast Survey, 1851) indicates no appreciable change in the number or location of the Little Lagoon deposits during the last hundred years. Several triangular structures are present on the inshore margin of the barrier island near Melbourne on the east coast of Florida.

Another possible occurrence is the group of cuspate deposits at Coatue Beach, Nantucket Island, which Shaler (1889) attributed to tidal whirlpools and Gulliver (1904) to current eddies caused by the tide. More recently, Johnson (1925, p. 438–446) and Raisz (1934, p. 842, 844) have described these deposits as successive recurved points of a compound spit modified by normal wave action. Here the most northern deposits, especially Bass Point, resemble the St. Lawrence features in having no recurving ridges associated with them. As Raisz

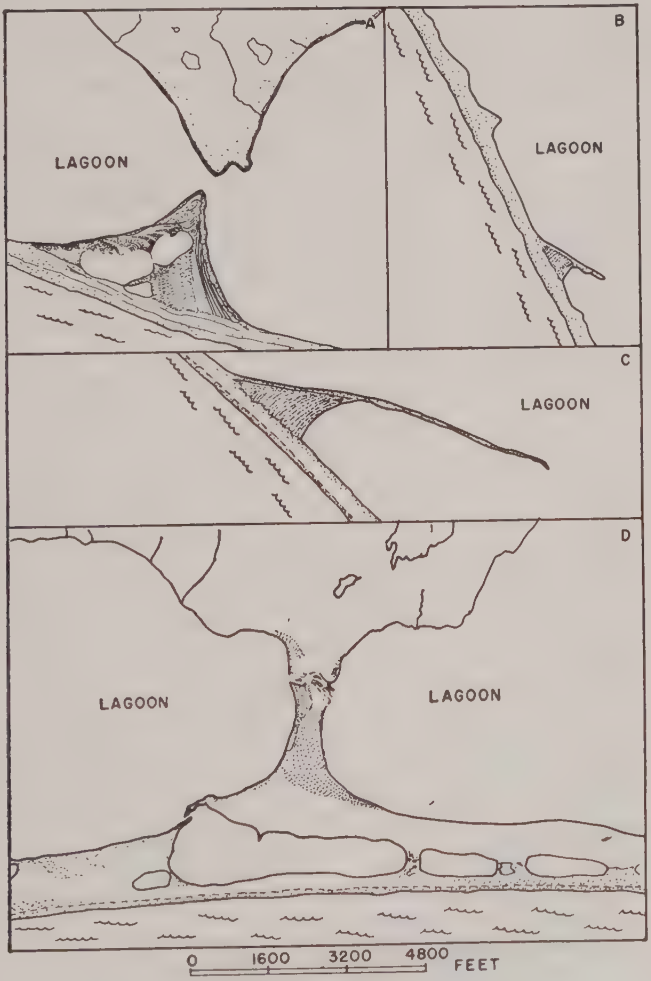

Fig. 3.—Selected St. Lawrence Island cuspate spits

points out, this lack may be due to truncation of the recurved tip of the spit.

POSSIBLE MODES OF ORIGIN

At the present stage of investigation, no mode of origin can be definitely assigned to the cuspate spits. Several explanations are offered, and the evidence for or against each is reviewed.

EDDY CURRENTS

Brown (1902), discussing Gaspée Point, a cuspate foreland in Rhode Island, suggests formation by deposition in the area of still water between adjacent eddy-current cells. According to Brown, sediment is carried outward from the base along one limb and deposited in the area of still water or is picked up at the apex by another eddy flowing toward the base, thus completing the triangle (fig. 4, *A*). Stream deposition and overwash from the lagoon across the limbs would fill in the middle. Such a current pattern is contrary to that observed at the type locality on St. Lawrence Island, where feeble currents were moving from base to apex along both limbs. However, these currents may have been set up by the moderate southerly winds characteristic

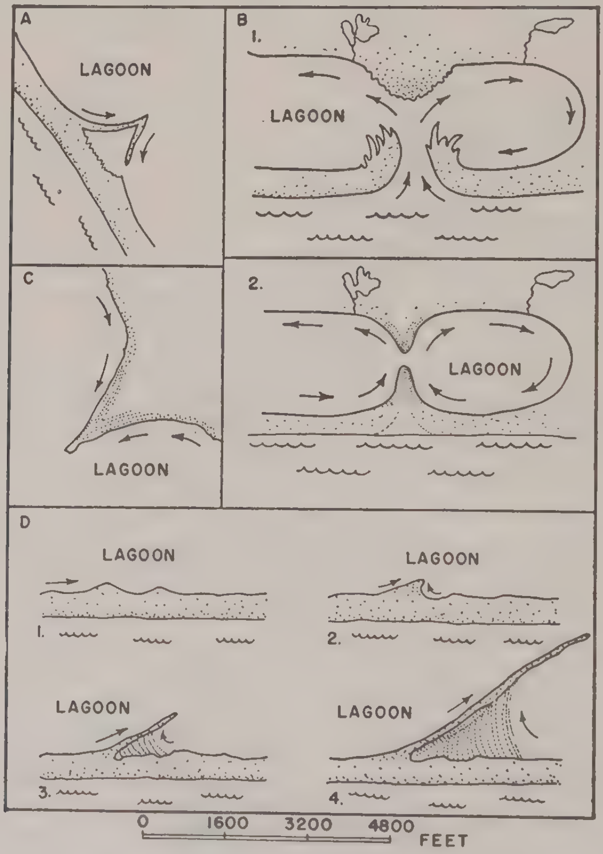

FIG. 4.—Current patterns for the suggested modes of origin of the St. Lawrence Island cuspate spits

of the summer months and may not be wholly representative. The unequal development of the limbs of the smaller spit of the pair studied (pl. 1) may be cited as indirect evidence of base-to-apex transport as the chief process in building such a spit. The rudimentary development of the west limb may be due to interruption of beach drift by the deep channel of the sluggish stream entering near by. The stream channel may act as a settling basin, effectively cutting off sediment. Though broad at the mouth this short stream drains a swamp and brings very little sediment into the lagoon.

Rotary currents, such as those postulated by Cooke (1934, p. 91) for the Carolina Bays, could build the paired cuspate spits, one seaward from the mainland, the other landward from the barrier beach. Cooke suggested that these currents would be set up by wind blowing from nearly the same direction over long periods of time. In such a horizontal cell, that is, a cell with a vertical axis, the surface current would be flowing against the wind as much as with it. Studies in shallow water have shown, however, that cells with horizontal axes nearly perpendicular to the wind direction and with a bottom return flowing toward the wind are more likely to form under such wind conditions (von Arx, 1948, p. 863). The slight offset present in every occurrence of paired spits argues against a single rotary current's extending across the lagoon, though adjacent major and minor cells might result in the observed relations. Transfer of water with the changing tides would help to maintain the offset as a channel.

DEPOSITION WITHIN WAVE SHADOWS

Another possibility is that the cuspate spits were formed before the barrier beach was completed, that is, when, if ever, it existed as a series of segments or sand keys around which waves were refracted and caused to meet and set up currents. Deposition of sediment might occur in wave shadows behind such segments. Such an origin might account for the wide, irregular spacing of the spits along the barrier beaches of St. Lawrence Island. However, in Little Lagoon, Alabama, and at Coatue Beach, Nantucket, the spits are closely spaced side by side, some actually touching one another along the base lines. This mode of origin also fails to account for the spits lying along the mainland when no counterpart is developed on the bar opposite. In addition, it is doubtful that such long, uniform, very gently arcuate barrier beaches as those of St. Lawrence Island would result from the connection of several once more or less independent islands or keys. It seems much more likely that such structures would result from deposition under the influence of a longshore current.

DEPOSITION AFTER BREACHING OF LAGOON BARRIER

The paired cuspate spits may result from deposition of sediment washed through old channels in the barrier beach, with subsequent modification after the breach is healed (fig. 4, *B*). Breaching by storm waves at several points along the beach would account for the irregular spacing of the spits This suggestion explains the original deposition of paired sand masses and is in agreement with observations that lagoon entrances can shift rapidly. It is difficult, however, to explain by this mechanism the progressive increase in size of the spits, as recorded by the delicate growth lines or the ponds within most St. Lawrence Island spits. In addition, the height and width of the barrier beach are nearly constant along the base of the spit, and no good evidence for a former opening is present in the examples studied.

LONGSHORE SEDIMENT DRIFT

Cuspate spits lying on the mainland side of the lagoon and bordered by shoreline indentations are probably built by sediment carried past the projection of the shore by longshore drift (fig. 4, *C*).

The suggestion by Johnson (1925, p. 445) that large cuspate deposits on the lagoon side of barrier beaches are formed as successive recurved points of the barrier finds little support in the St. Lawrence Island spits. In only one instance (fig. 4, *A*) is the barrier itself widened near the spit. Even here the beach ridges are essentially parallel to the seaward edge of the barrier beach, and the western limb of the spit is a curved prolongation composed of material transported from a projection on the inside of the barrier beach. The other St. Lawrence spits definitely appear to have been built on a continuous barrier beach. This is substantiated by the parallelism of the lagoon shore line and seaward shore line of the barrier beach and especially by the absence of thickening of the barrier beach into the ponds within the spits. Some evidence of such thickening into the ponds would be expected to remain, even if the barrier beach had migrated toward the mainland since spit formation. Lastly, the "growth lines" preserved within several of the ponds show that the spits initially were small in relation to the barrier beaches.

DEFLECTION OF CURRENTS BY SEDIMENTS WASHED OVER LAGOON BARRIER

The cuspate spits on the lagoon side of the barrier beach may originate from overwash of the barrier by storm waves, which deposit an irregular mass of material on the lagoon shore. This mass of sediment would deflect the major currents of the lagoon away from the barrier, and a spit meeting the barrier at an acute angle would be built in the direction of the deflected current (fig. 4, *D*). Material scoured from the barrier would move out toward the end of the spit, accounting for the narrowing of the barrier near its juncture with the spit, as is observed in several of the St. Lawrence Island localities. Simultaneously, eddies set up in the lee of the spit would scour material from the barrier and deposit it between the spit and the barrier, thus building an asymmetrical spit, recurved in the direction of the major current flow. Such deposition in the lee of the spit would result in a series of "growth lines" as the spit increased in length. Where "growth lines" are present, they include a set of subparallel ridges of differing length which meet the parent-bar at a large angle and are tangent to the initial limb at an old apex (fig. 4, *D*). In addition, there is often a less-well-developed series of lines conformable with the spit or initial limb, recording growth or slight shifts in its position. Such a cuspate spit would tend to extend itself, increasing in its deflecting capacity as it grew in size.

Sediment transport from barrier beach toward apex is indicated by the sorting that grows more perfect away from the barrier beach on the northwest limb of the sampled cuspate spit. The increase in mean grain size in this direction, however, runs counter to expectations based on beach studies, which show that smaller grains tend to outrun larger grains along many beaches (see, e.g., Krumbein, 1944, p. 17, 22). It is possible, however, that maximum currents are not present near the barrier because of frictional effects and that the large size of the grains from point *E* (fig. 2, inset) indicates that here the main down-lagoon current becomes critical. Possibly, large waves are not present along the spit near its juncture with the barrier beach because of the limited fetch with a southerly wind. Farther out on the spit, fine material might be winnowed out, improving the sorting and increasing the median diameter of the sediment. The more usual relations between size and sorting (Inman, 1949) may hold for the southeast side.

Agencies other than overwash might cause deflection of the currents. Constriction of the lagoon by a projection of the mainland might result in scour of the barrier beach, with deposition slightly farther along. Such an irregularity would deflect currents in the same manner as would sediments washed over the barrier beach. In the St. Lawrence Island occurrences, several of the cuspate spits and especially the paired spits lie where the lagoon is narrow. In one such pair, overwash or breaching of the barrier is ruled out by the presence of a series of lakes lying within the barrier and presumably antedating formation of the cuspate spits (fig. 3, *D*).

Whatever the determinant of the cuspate shape, the probable method of transport of grains along the limbs of the spits is longshore beach drift by wave swash, as described by Johnson (1919, p. 94–103). Here swash from waves approaching the shore obliquely carries grains in zigzag or parabolic paths along the foreshore. Such drift can move coarse sediment even if the associated longshore currents are small in magnitude. Shifting of sediment by this process was observed at the St. Lawrence spit localities.

CONCLUSIONS

The author suggests that transport by currents in the lagoon deflected by sediment carried over the barrier during storms is the most likely mode of origin of the St. Lawrence Island cuspate spits. These currents, resulting from tidal action or rivers entering the lagoon, would shape the spit as it lengthened by the addition of longshore beach drift.

The foregoing treatment of the St. Lawrence Island cuspate spits is intended to call to the attention of geologists a hitherto neglected, though very spectacular, shore-line structure. It is hoped that such spits will be recognized and studied in a number of more accessible localities, where more detailed current and sampling studies may be made and the several modes of origin suggested above tested in the field.

Observations of lagoon currents and sediment distribution in response to tides and shore-line configuration over a period of several months may demonstrate that depth, volume of water, or barrier-beach-to-mainland distance, for example, are more significant factors for cuspate spit formation than are current velocity and circulation. A series of scale-model tank studies might prove valuable.

ACKNOWLEDGMENTS.—The writer wishes to thank William L. Basham and Harry B. Allen for aid in field observations and sample collection. William C. Krumbein, of Northwestern University, contributed suggestions in the interpretation of mechanical-analysis results. Robert P. Sharp, of the California Institute of Technology, and Francis P. Shepard and Douglas L. Inman, of the Scripps Institution of Oceanography, read the manuscript and made suggestions concerning mode of origin of the cuspate spits. Donald B. Sayner prepared the illustrations.

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BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
VOL. 66 MAY 1955

NEUTRON-IRRADIATED QUARTZ AS A TRACER OF SAND MOVEMENTS*

BY EDWARD D. GOLDBERG AND DOUGLAS L. INMAN

The Problem

Geologists have long felt the need for a tracer of sand movements in nature. Two classes of tracers have been employed with limited success. The first utilizes an external component added to the sand under study—*i.e.*, colored glasses or minerals not found in the environment under investigation. However, the size distributions, densities, and shapes of such tracers do not conform exactly to these properties in the natural components in the sand, and such characteristics determine the nature and amount of transport under the influence of fluid movement.

The second group of tracers utilizes natural components in the sand, such as rare minerals. In the relatively few environments in which techniques employing rare minerals can be applied, their use is limited to qualitative studies and is difficult to apply because it requires a detailed knowledge of the existing distribution of the trace mineral over the area to be studied. At best such tracers give information applicable only to particles of similar size, shape, and density, and thus do not apply to the major fractions of the sand. The treatment of a natural component to render it readily distinguishable has rarely been successful. The literature is replete with examples of dyed quartz, etched quartz, silvered quartz, etc. However, such tracers are usually either difficult to distinguish from the untreated grains, or the treatment is but temporal.

The natural tracer of sand movements should be: (1) of the same size distribution, density and shape as one of the major components under study, (2) easily and rapidly distinguishable from the sand mass, (3) available in relatively large amounts, (4) inexpensive, (5) able to retain its distinguishing properties over times comparable to the times of the fluid processes.

Since quartz is one of the dominant components of most sands, a method of tagging it should be highly desirable. Quartz can be concentrated from a sand by heavy-liquid, magnetic, electrostatic, or other separation techniques. Hence, quartz was subjected to slow neutron irradiation to ascertain if this treatment would bring about changes in the properties of the quartz such as induced radioactivity or color changes which would identify the quartz.

Experimental

Five-gram samples of quartz separated from the St. Peter sandstone were irradiated in the slow-neutron pile of the Oak Ridge National Laboratory for periods of 2 hours, 8 hours, 1 day, and 1 week under a rated flux of 10^{11} neutrons/cm^2/sec. Two weeks after removal from the pile the samples were assayed for their beta and gamma activities utilizing an end-window Geiger-Müller counter with a window thickness of 1.4 mg/cm^2.

From activity measurements for 2½ months the half-life of all samples was of the order of 15 days. In the sample subjected to an irradiation of 1 week, a longer-lived activity appeared during the second month. This latter activity was not identified. An aluminum absorption curve indicated a beta ray with a maximum energy of 1.6 Mev with essentially no gamma radiation present (less than ½ per cent of the total activity). From the above absorption and decay characteristics, the main activity is uniquely identified as phosphorus − 32. Turkevich and Samuels (1954) reported small amounts of P − 32 activity in similarly irradiated quartz.

The activity could not be removed by im-

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* Contribution from the Scripps Institution of Oceanography, New Series No. 761. This study was sponsored by the Office of Naval Research and the Beach Erosion Board under contracts with the University of California.

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mersing the quartz grains in sea water and shaking the mixture for periods up to 2 weeks.

A slight color change toward buff was observed between the quartz irradiated for 1 week and the nonirradiated quartz. However, it was impossible to distinguish individual particles of irradiated from the nonirradiated quartz on the basis of color or any change in optical properties.

Tyler (1936) reported that apatite is the major inclusion in the St. Peter sandstone. More recently, Loewenstein (1954) pointed out that phosphates often accompany aluminum oxides in a twin substitution for the silicate tetrahedra. Microscopic examinations of the irradiated quartz were inconclusive with respect to apatite inclusions.

The phosphorus content of the St. Peter sandstone was determined spectrophotometrically as 250 parts per million by weight. Another value similarly determined for a sample of quartz sand from the barrier beach on Santa Rosa Island, Gulf Coast of Florida, was 620 parts per million by weight of phosphorus. Thus, quartz with phosphorus concentrations of these orders of magnitude can be readily irradiated to form a satisfactory tracer.

Sensitivity

Single grains of quartz with diameters or longest dimensions of approximately 0.1 mm were taken from the sample irradiated for 1 week and mixed with about a million inactive sand grains. The mixture was coated on an 8½ by 11-inch cellophane sheet which was moistened with thin lacquer. The cellophane, uncoated side down, was placed upon a sheet of Kodak "No-Screen" X-ray film for 4 days and then developed. The active grain was readily identified. Active grains were also identified in experiments with more than one irradiated grain per million inactive grains.

Discussion and Conclusion

Quartz containing phosphorus fulfills all the proposed qualifications for tracers. By increasing the irradiation time or using a higher irradiation flux, exposures of 1 or 2 days or less should be adequate to give recognizable darkening of the photographic paper. Experiments can be carried out over at least four half-lives (about 2 months) of the phosphorus. In the later part of such an extended period, longer exposures become necessary.

However, at this point health considerations enter. Although the half-life of the phosphorus is short enough to eliminate any large-scale contamination problems, it is of interest to consider the amounts of activity to be dealt with in hypothetical problems.

Assuming that detection of one grain in a million is possible, a well-sorted natural beach sand with an average particle diameter of 0.2 mm and a total porosity of 44 per cent could be traced if it contained approximately 10^5 irradiated quartz particles or 1.1 grams/cubic yard of sand. At Santa Barbara, California, where the littoral transport of beach sand, averaged over a 10-year period, is approximately 770 cubic yards per day (Johnson, 1953), 25.4 kg of irradiated quartz sand, if completely dispersed, would be sufficient to tag the sand transport past a point on the beach during a 30-day period.

Considering the sample that was irradiated for 1 week, we have 4000 counts per minute/0.10 g of sample at a counting geometry of 5 per cent. This is equivalent to 765,000 disintegrations per minute/gram or approximately ½ millicurie per kilogram or ½ curie/ton. In the example cited above, 13 millicuries would be necessary for a single experiment.

This amount of activity concentrated in one unit before dilution may constitute a health hazard. However, once diluted with about 50 or more parts of inactive material, no health hazard appears imminent. It is apparent that no danger will be encountered in experiments with smaller-scale natural phenomena, where lesser amounts of active material are required. These considerations assume a clean separation of the quartz from such minerals as feldspars and micas. The latter substances can contain elements such as potassium, sodium, and calcium which upon neutron irradiation give rise to high or long-lived activities.

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SCRIPPS INSTITUTION OF OCEANOGRAPHY, LA JOLLA, CALIF.

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Two New Pelagic Tunicates from the Eastern Pacific Ocean[1]

LEO D. BERNER[2]

THE SPECIES here named *Cyclosalpa strongylenteron* was first noted in a plankton sample taken at station 194 of Scripps Institution of Oceanography (SIO) cruise Shellback (SB). This species has since been identified from seven other Shellback stations and from four Marine Life Research (MLR) stations.

Cyclosalpa pinnata quadriluminis, though not previously named, has been described by Ihle (1910: 18–19) and Komai (1932: 69–70) as an aberrant form. In the MLR area, which extends from the Columbia River to the southern tip of Baja California and four hundred miles out to sea, this subspecies has been taken in such numbers and so consistently that a re-examination of these presumed aberrant individuals is felt necessary. Here for the first time it is named and reported in large numbers.

The following material, upon which part of the descriptions herein are based, has been deposited in the U. S. National Museum:

1. *Cyclosalpa strongylenteron*, aggregate generation, HOLOTYPE, 1 specimen U.S.N.M. 11281.
2. *Cyclosalpa strongylenteron*, solitary generation (embryo), PARATYPE, 1 specimen U.S.N.M. 11282.
3. *Cyclosalpa strongylenteron*, aggregate generation, PARATYPES, 10 specimens U.S.N.M. 11283.
4. *Cyclosalpa pinnata quadriluminis*, aggregate generation, HOLOTYPE, 1 specimen U.S.N.M. 11284.
5. *Cyclosalpa pinnata quadriluminis*, aggregate generation, PARATYPES, 5 specimens U.S.N.M. 11285.

I wish to express my thanks to Drs. M. W. Johnson and C. L. Hubbs for their advice in preparing this manuscript and to Dr. Paul Friedlander for his assistance in naming the animals.

Cyclosalpa strongylenteron new species

The aggregate generation of this species was first recognized in a sample taken at SIO SB station 194, 0° 01.5′ S and 99° 08.5′ W. In a subsequent preliminary survey it was found at seven other SB stations and at four MLR stations (Fig. 8). Embryos of the solitary generation have been observed at MLR stations 11–120.80 and 35–110.60. The details of these individuals were almost completely obscured by a granular appearing mantle but the stolons were well preserved and the details of well-developed aggregate individuals could be readily determined.

Cyclosalpa strongylenteron, aggregate generation

The aggregate generation of this species shows characters quite similar to those of the aggregate generation of four other species. The musculature resembles that of *C. pinnata*, the major difference being the presence in *C. strongylenteron* of a large dorsal visceral muscle and only two sphincters on the lower lip of the oral opening. It resembles *C. affinis* in the convoluted formation of the dorsal tubercle and the looped nature of the gut. The caecum is large and projects posteriorly much like that found in *C. bakeri*. The arrangement of the testis is reminiscent of that found in *C. virgula* in that it extends back from the center of the gut loop in a long slender pouch.

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[1] Contribution from Scripps Institution of Oceanography, New series No. 762. Manuscript received June 21, 1954.

[2] Scripps Institution of Oceanography, University of California, La Jolla, California.

The terminal openings and long muscular peduncle differentiate this species from all other members of the genus *Cyclosalpa* except *C. pinnata* and *C. bakeri*. The absence of light organs differentiates *C. strongylenteron* from *C. pinnata* and the convoluted dorsal tubercle and formation of the body muscles distinguish it from *C. bakeri*.

Body: (Fig. 1) The general shape of the body is much like that of the aggregate generation of *C. affinis*. The size is from 2 to 100 mm. The test is soft, thick and very easily stripped from the animal. The atrial and oral openings are terminal. Many specimens have the dorsal portion of the body covered with a granular material which makes the details of structure difficult and sometimes impossible to see.

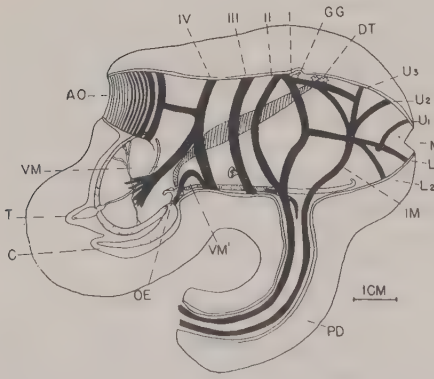


FIG. 1. *Cyclosalpa strongylenteron*, aggregate generation. AO, Atrial opening; C, caecum; DT, dorsal tubercle; GG, dorsal ganglion; IM, intermediate muscle; L_1-L_2, sphincters of the lower lip; M, oral opening; OE, oesophagus; PD, peduncle; T, testis; U_1-U_3, sphincters of the upper lip; VM, dorsal visceral muscle; VM′, ventral visceral muscle; I-IV, body muscles.

Light organs: Light organs are absent.

Muscles: (Fig. 1) There are four body muscles arranged much like those of *C. pinnata*. All the body muscles are continuous across the dorsal midline, while ventrally only muscle IV is continuous with its mate from the opposite side. Body muscles I and II are in contact both dorsally and ventrally, extending ventrally into the peduncle as the paired posterior peduncle muscles. Muscle IV gives off two branches, the first the ventral visceral muscle, originates ventrolaterally and extends back along the intestine. The second, the dorsal visceral muscle, originates just below the lateral midline and extends posteriorly and ventrally into the center of the loop formed by the gut. Just above the origin of the dorsal visceral muscle the atrial retractor attaches to muscle IV; from whence it extends back to insert into the first, and strongest, atrial sphincter. The atrial sphincter muscles, which number about 13, are unbranched and form complete loops.

The oral musculature closely resembles that of the aggregate *C. pinnata*. There is a single oral retractor which passes forward, external to the intermediate muscle, and bifurcates to form the two sphincters of the lower lip. The upper lip has three sphincters, the first originates from the first sphincter of the lower lip just after its formation. The second and third originate from the intermediate muscle just above the point where it is crossed by the oral retractor. From the point of origin of the sphincters the intermediate muscle bends back to attach to the dorsal portion of the first body muscle. The horizontal muscle extends from the intermediate muscle, just before the junction of that muscle with body muslce I, to a point on the third sphincter of the upper lip about midway between its origin and the dorsal midline. Ventrally the intermediate muscle joins its mate from the opposite side to form a V which extends into the peduncle as the anterior peduncle muscle.

Dorsal tubercle: (Fig. 2) The dorsal tubercle is much twisted, forming an almost closed irregular ring.

Internal structure: The gut approaches in shape most closely that found in the aggregate generation of *C. affinis*. It forms a large loop which lies outside the body in a large protuberence, the postabdomen. The wide flairing oesophageal opening is on the right side of the body at the base of the gill. The anus is on the left side slightly above the oesophageal opening. There is no stomach-like enlargement of the intestine. The caecum, similar to that in *C. bakeri*, is extremely well developed, originating just behind the opening of the oesophagus and extending back at least as far as the end of the postabdomen. The duct of the intestinal gland, which empties into the intestine just after the origin of the caecum, passes across the gut loop and branches over the distal portion of the intestine. The endostyle extends from below the bifurcation of the oral retractor to the area of the oesophageal opening. The heart is below and slightly anterior to the opening of the oesophagus. The ganglion is quite similar to that of the aggregate *C. pinnata*. The testis is in a slender pouch extending posteriorly from the region midway around the gut loop. It may be as much as three times as long as shown in Figure 1. The vas deferens extends across the gut loop and up into the region just anterior to the atrial opening. The ovary lies just behind muscle III. The oviduct passes forward to a point near the anterior border of that muscle.

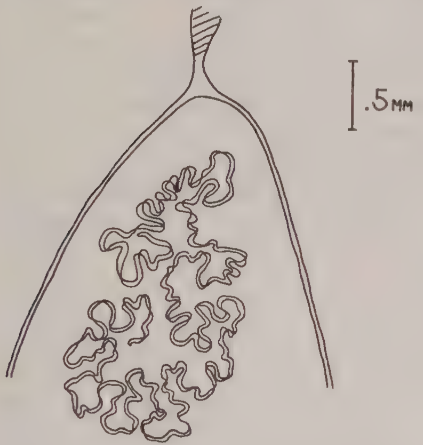


Fig. 2. *Cyclosalpa strongylenteron*, dorsal tubercle.

Cyclosalpa strongylenteron, solitary generation

The solitary generation of this species has to my knowledge been taken only twice: seven embryo individuals, with well-developed stolons, at MLR station 11–120.80 and one embryo at MLR station 35–110.60. These all have the same granular appearance seen in some aggregate individuals. Here the granular appearance is so well developed that it conceals many details of structure. So little of the details of the body muscles of the solitary generation can be determined, due to concealment by this granulation, that it is impossible to compare them, except in a general way, with those of existing species.

Body: (Fig. 3) Length 25 mm. The body is cylindrical with the oral and atrial openings terminal. There are two well-developed ventral languets below and just posterior to the oral opening. The test appears more ridged than that of the aggregate form.

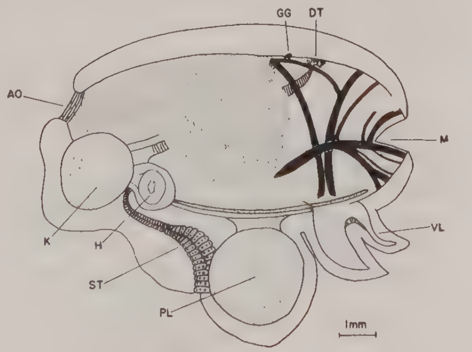


Fig. 3. *Cyclosalpa strongylenteron*, embryo of solitary generation. AO, Atrial opening; DT, dorsal tubercle; GG, dorsal ganglion; H, heart; K, eleoblast; M, oral opening; PL, placenta; ST, stolon; VL, ventral languets.

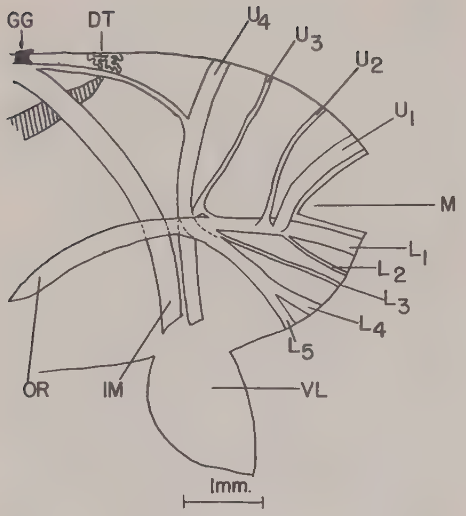


FIG. 4. *Cyclosalpa strongylenteron*, solitary generation, oral musculature. DT, Dorsal tubercle; GG, dorsal ganglion; IM, intermediate muscle; L_1-L_5, sphincters of the lower lip; M, oral opening; OR, oral retractor; U_1-U_4, sphincters of the upper lip; VL, ventral languet.

Light organs: It could not be determined whether or not light organs were present.

Muscles: (Figs. 3 and 4) There appear to be seven body muscles arranged in a manner much more complicated than in other species of the genus. All the body muscles are interrupted ventrally and appear to form two bundles dorsally.

The oral musculature could be determined on the embryo taken at station 35–110.60, it is more complicated than that of any of the other cyclosalpas (Fig. 4). There are five sphincters on the lower lip and four on the upper lip. There is a single oral retractor which passes forward external to the intermediate muscle and bifurcates into a dorsal and a ventral portion. The dorsal portion continues forward to form the first ventral oral sphincter (L_1), midway along its course a small muscle branches off to form L_2. The ventral branch of the oral retractor gives off a thin branch, just after its formation, which continues forward to form L_3. The remaining portion of the ventral branch then bifurcates to form L_4 and L_5. The first two sphincters of the upper lip, U_1 and U_2, originate from the first sphincter of the lower lip midway between its origin and the origin of L_2. U_3 is formed from two portions, one coming from U_4 just as it emerges from under the oral retractor and the other from the oral retractor just before its bifurcation. A branch from the ventral portion of the oral retractor and an independent muscle which runs parallel to the intermediate muscle join under the oral retractor and continue dorsally as U_4. Near the dorsal midline U_4 gives off a branch which turns posteriorly and joins the intermediate muscle in the region of the dorsal ganglion.

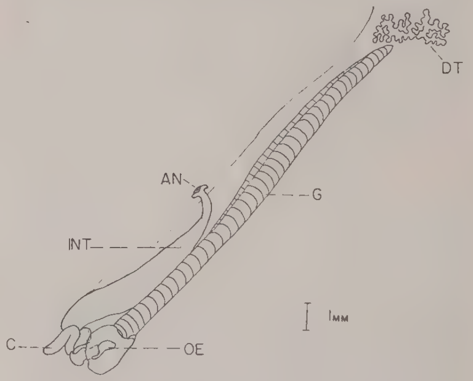


FIG. 5. *Cyclosalpa strongylenteron*, gill and gut of solitary generation. AN, Anus; C, caecum; DT, dorsal tubercle; G, gill; INT, intestine; OE, oesophageal opening.

The atrial musculature appears to be much like that of the solitary *C. affinis*.

Dorsal tubercle: The dorsal tubercle is almost identical with that of the aggregate form, a condition approached but not obtained in *C. affinis*.

Internal structure: The gut, as is typical of all solitary cyclosalpas, is dorsal to the gill, but uniquely it overlays just slightly less than half the length of the gill (Fig. 5). The wide flairing oesophageal opening lies at the ven-

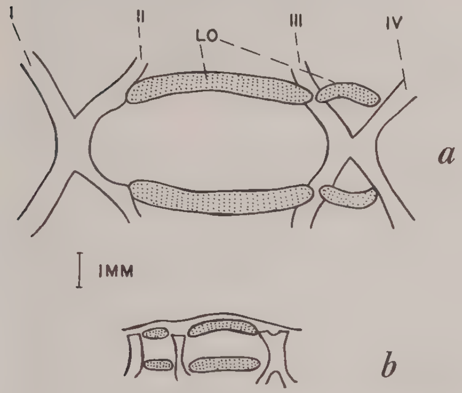


FIG. 6. *a*, *Cyclosalpa pinnata quadriluminis*, aggregate generation, dorsal view showing arrangement of body muscles and light organs. LO, Light organs. *b*, *Cyclosalpa pinnata* aberrant form after Ihle (1910).

tral posterior end of the gill. The narrow oesophagus forms a single spiral before continuing into the intestine. The first part of the intestine is enlarged into what may be called a stomach. Two blunt caeca, of equal size, project posteriorly from their origin on the intestine immediately behind the oesophagus, on either side of the midline. The endostyle extends from the area of the oesophageal opening to the anterior part of the body. The ganglion, much like that of the solitary *C. pinnata*, has a well-developed, horseshoe-shaped eye. The heart lies anterior and ventral to the oesophageal opening. The stolon originates near the heart and extends forward to a point half way up the body, where it turns directly away from the body.

Distributional data on *C. strongylenteron* are very scattered since the species has been identified from only 12 localities. The range is from off the coast of Peru to off the coast of Baja California (Fig. 8). Since the surface temperatures at these localities ranged from 14.5 ° C. to 28° C. the species appears to be eurythermal. More information on its vertical distribution, however, may indicate a more limited temperature range.

Cyclosalpa pinnata quadriluminis
new subspecies

Cyclosalpa pinnata (Forskål), 1775, the first of the salps described, is probably the best known species of the family. It appears also to be the most variable, inasmuch as it includes at the present time two subspecies in addition to the one described in this paper.

In his report on the Siboga collections Ihle (1910: 18–19) figured one aberrant specimen of the aggregate generation of *C. pinnata* that had two pairs of light organs instead of the usual single pair (Fig. 6*b*). This aberrant type was also reported by Komai (1932: 69–70), who found a single specimen in the vicinity of Seto, Japan.

The aberrant type, which is here given the name *Cyclosalpa pinnata quadriluminis*, occurs consistently in the plankton samples taken by Scripps Institution of Oceanography in conjunction with the MLR program. The aggregate generation of *C. pinnata* has been found in 49 of 1,158 hauls examined. From these hauls 104 specimens of *C. pinnata polae* and 620 specimens of *C. pinnata quadriluminis* have been recorded. No specimens of the aggregate generation of *C. pinnata pinnata* have been observed. The subspecies *quadriluminis* agrees in all respects with the subspecies *polae* except that there is an additional pair of light organs present in *quadriluminis*.

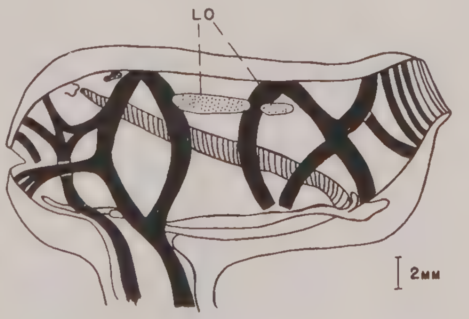
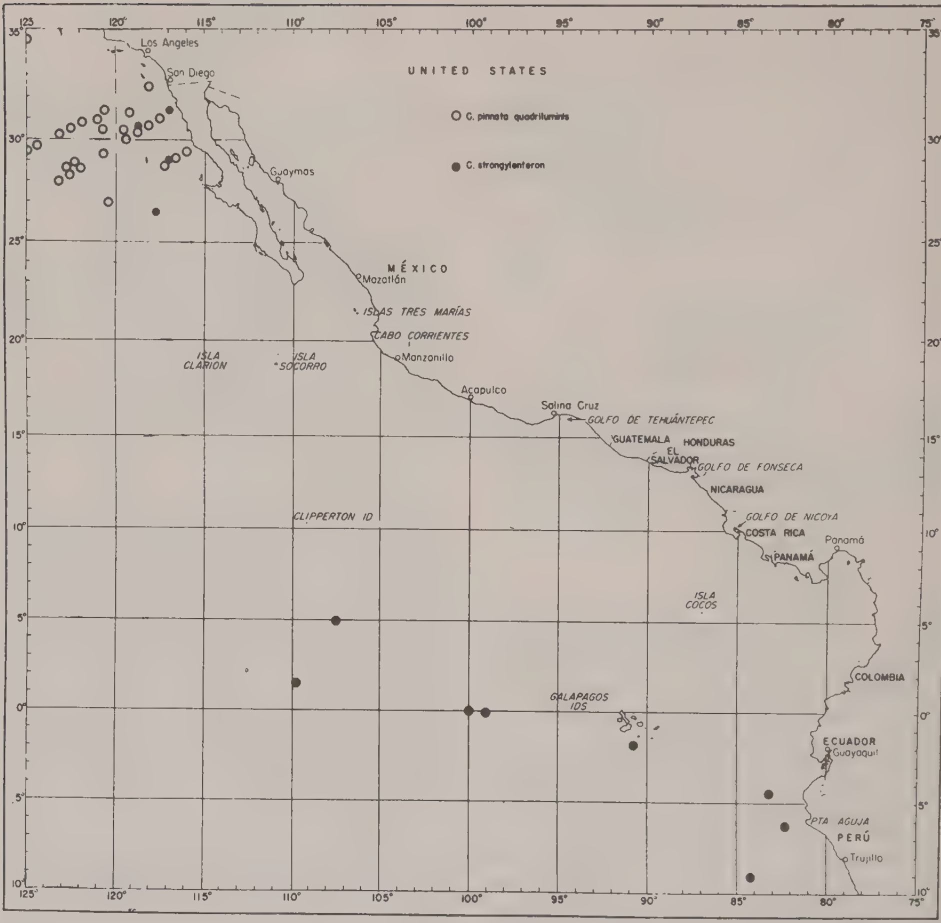


FIG. 7. *Cyclosalpa pinnata quadriluminis*, aggregate generation. LO, Light organs.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Los Angeles
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UNITED STATES
○ C. pinnata quadriluminis
● C. strongylenteron
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MÉXICO
Mazatlán
ISLAS TRES MARÍAS
CABO CORRIENTES
Manzanillo
ISLA CLARION
ISLA SOCORRO
Acapulco
Salina Cruz
GOLFO DE TEHUÁNTEPEC
GUATEMALA
HONDURAS
EL SALVADOR
GOLFO DE FONSECA
NICARAGUA
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GOLFO DE NICOYA
COSTA RICA
Panamá
PANAMÁ
ISLA COCOS
COLOMBIA
GALAPAGOS IDS
ECUADOR
Guayaquil
PTA AGUJA
PERÚ
Trujillo

FIG. 8. Chart showing distribution of *Cyclosalpa strongylenteron* and *Cyclosalpa pinnata quadriluminis.*

Cyclosalpa pinnata quadriluminis, aggregate generation

Body: (Fig. 7) The body exhibits the typical shape of the aggregate generation of *C. pinnata* but the test is thicker than generally found in the species. The size of the specimens ranged from 10 to 50 mm.

Muscles: The four body muscles are all continuous dorsally. Muscles I and II and muscles III and IV are fused for a short distance over the dorsal midline (Fig. 6*a*). In the specimens examined this fusion does not extend as far as indicated for *polae* by the figures of Sigl (1912: 66–74) and Sewell (1926: 72). Body muscles I and II fuse ventrally and continue into the peduncle as the posterior peduncle muscles. The single oral retractor branches to form the three sphincters of the lower lip. Of the three dorsal oral sphincters the first is an independent muscle while the second and third originate from the intermediate muscle just above the point where the oral retractor crosses it. Dorsally the intermediate muscles unite with the first body muscle; midventrally they join and continue into the peduncle as the anterior peduncle muscles.

Internal structure: The internal structure appears to be identical with that of the aggregate *C. pinnata*. The gut lies below the endostyle, which extends forward to the area of the third ventral oral sphincter. The dorsal tubercle is of typical horseshoe-shape and the ganglion with the eye is typical of the species.

Light organs: (Fig. 6*a*, *b*) It is on the variation found in the light organs that this subspecies is based. The usual pair of light organs is present between muscles II and III but there is an additional pair situated between muscles III and IV. The second pair of light organs is smaller than the first, usually about one third as large.

No characters have been found in individuals of the solitary generation examined which might indicate that they belong to this subspecies. The specimens examined have been typical of the solitary form of *C. pinnata polae*.

Except for the records of Ihle and Komai from the Molucca Sea and off Seto, Japan, respectively, the known distribution of *C. pinnata quadriluminis* at the present time is confined to the area off the California coast south of Point Conception and north of Sebastián Viscaíno Bay off Baja California (Fig. 8). In the area off western North America under consideration the subspecies is six times as common as subspecies *polae*. No information is available on the vertical distribution of the subspecies.

SUMMARY

Two members of the genus *Cyclosalpa* have been described from the eastern Pacific Ocean. *C. strongylenteron*, new species, has been taken in 12 localities ranging from off the coast of Peru to off the coast of Baja California. *C. pinnata quadriluminis* new subspecies, previously noted by Ihle and Komai is here named and reported in large numbers for the first time. The range of this subspecies, except for the two specimens previously reported, is off southern California and northern Baja California.

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Reprinted from THE CONDOR, Vol. 57, No. 2, March-April, 1955
(issued March 30), pp. 121-122.

Black Scoters Reported from Baja California.—As I have seen all three species of scoters along the northwestern coast of Baja California and as all three have been reported wintering south to San Diego County, California (Grinnell and Miller, Pac. Coast Avif. No. 27, 1944: 89–91), it is surprising to find no record of the Black Scoter or American Scoter (*Oidemia nigra*) from Baja California or elsewhere in México. It is not included in the treatises by Grinnell (Univ. Calif. Publ. Zool., 32, 1928:77), by Friedmann, Griscom, and Moore (Pac. Coast Avif. No. 29, 1950:45), or by Blake

(Birds of Mexico, 1953:58–59). Two definite records of this species are for 3 to 4 miles and 6 to 7 miles south of the mouth of Río Vicente (or Río San Isidro), respectively, on April 10 (one male, alone), and on August 8, 1954 (several males, in a raft of scoters including also at least one male Surf Scoter). On each occasion the birds were at rather close range in the surf.

The occurrence of this cool-water species in Baja California was to be expected, as the inshore temperatures of the northern part of the outer coast of Baja California are generally lower than those encountered along most of the southern California shoreline. Because of the cool upwelled water, many marine organisms of various groups that reach the San Diego region, and even some that skip that warmer area, are being found to occur in Baja California, and it is to be anticipated that nearly all of the northern types that reach the San Diego area will eventually be found to occur in the cooler stretches of the coast of northwestern Baja California.

The record of August 8 is much earlier than any reported from California, according to the listing by Grinnell and Miller (Pac. Coast Avif. No. 27, 1944:90–91). Their summary of the known records encompasses the months from November to April. It is possible that the August bird, like a few Surf Scoters and a few White-winged Scoters, was a non-migrating individual—CARL L. HUBBS, *Scripps Institution of Oceanography, University of California, La Jolla, California, November 8, 1954.*

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Reprinted from SCIENCE, Vol. 121, March 18, 1955.

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Visual Detection of Temperature-Density Discontinuities in Water by Diving

Conrad Limbaugh and Andreas B. Rechnitzer
Scripps Institution of Oceanography,
La Jolla, California

Direct visual oceanographic observations of subsurface physical phenomena, formerly probed only by instrumentation, have gained impetus and have attained a much higher level of significance since the advent of such self-contained diving equipment as the Aqua-lung. Representatives of many of the scientific disciplines who participate in the study of the oceans have found a variety of uses for this direct method of observation, sampling, and measurement. Extensive free-diving research activities are carried on throughout the year at the Scripps Institution of Oceanography. The observation potential of the diving method of detecting, delimiting, and describing the temperature and other physical characters of water masses is, we hope, exemplified by the findings recorded here (*1*).

In certain areas, including places where the use of the bathythermograph (*2*) is difficult or inconvenient and where the water-mass pattern is on such fine scale that ordinary bathythermograph lowerings would likely miss important features, the thermocline and other phenomena can be detected visually and sensually by divers. Investigations of more oceanic waters by diving has been limited, but some information about the interfaces at thermoclines there has also been obtained (*3*).

Visual detection of the thermocline (or thermoclines) and of water-mass differences have been achieved in several ways: (i) indirectly by observing the vertical distribution of living organisms and other suspended particles, (ii) by viewing the refractory plane at the temperature-density discontinuity, and (iii) by the "stream" lines (refraction patterns) formed during the mixing of water masses of different density.

Frequently, plankton and leptopel (*4*) accumulate, so that they are readily visible at the temperature-density interface, where they are detained either above or below the discontinuity by the difference in water density. The groups of macroscopic animals

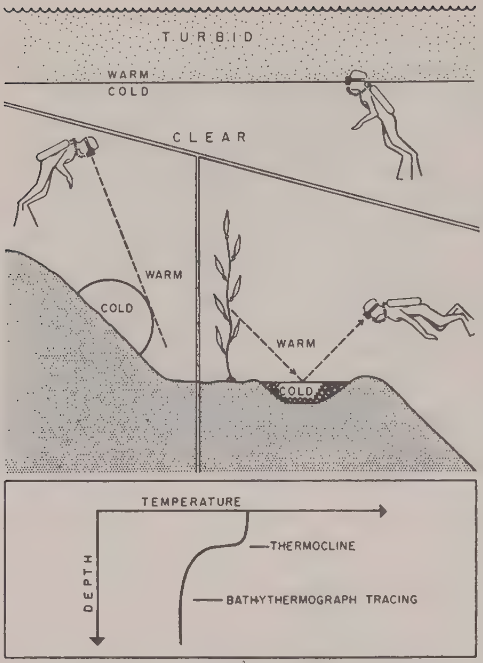

Fig. 1. Schematic representation of three temperature-density discontinuities observed by diving, with a bathythermogram appropriate for each of the temperature changes across the discontinuity.

that very frequently accompany such aggregations may be the only visible indications of a poorly defined thermocline. Patches of "red-water" resulting from blooms of *Gymnodinium* or *Prorocentrum* increase the turbidity of the surface layer, rendering it muddy and reducing visibility. The change to normally clear water below the turbid canopy at the thermocline, sometimes dramatically abrupt, clearly defines the location of the discontinuity. The concentrations of organic matter are most easily ascertained when the interface is near eye level (Fig. 1). Diving observations made in conjunction with simultaneous fathometer recordings of a diffuse near-surface reflection source have shown a definite agreement between the movements of the thermocline and of the associated living organisms and leptopel concentrations.

Difference in density between two water masses have been seen by us: (i) as a smooth, flat refractive plane of demarcation between two undisturbed water masses, and (ii) as an irregular boundary between two unstable masses undergoing mixing. The interface between two relatively quiescent masses of water is nearly parallel to the surface. Such a thermocline is best viewed by looking directly along the interfacial plane. Certain conditions, however, permit a greater angle of detection. A striking observation was made during the fall of 1953, at a time when the surface was calm and the water was clear. In the small tributaries at the head of the Scripps Submarine Canyon, at a depth of 100 ft, there are many small depressions containing trapped plant detritus. Among these accumulations of decaying vegetation were open areas with "pools" of turbid water, free of large pieces of matter. The upper surface of these clear areas in the depressions had a refractive-index differential great enough to reflect a mirror image of some kelp, *Macrocystis pyrifera,* which extended well above the surface of the depression (Fig., lower right). The entrapped water mass was only a few inches thick and, when probed by hand, was found to be markedly colder than the water above it. Other "mirror" pools were found in the vicinity, and all probably represented remaining portions of a cold water mass that had recently left the area. These pools are evidently transient phenomena, since they have seldom been observed.

On 19 September 1954, another interfacial discontinuity was seen near Avalon Harbor, Catalina Island. We descended to the steep sloping bottom at a depth of 60 ft without encountering a thermocline. Swimming along the bottom, however, we encountered an upwardly convex tongue of dense water 4 ft high and 10 ft wide, flowing parallel to the beach. The interface was well defined and easily discerned at any tangent across its surface. A sharp thermal gradient was noted as we penetrated the tongue, which exhibited refractive lines or patterns comparable to the mixing of two miscible liquids of unlike densities.

Unfortunately most of our underwater encounters with well-defined thermoclines and density discontinuities have been made without mechanical instruments or sampling devices, other than a depth gage, and were incidental to other objectives. The amount of oceanographic information available to the human sense is so great that each dive may reveal an enigma that can be only casually noted if the primary purpose of the dive is to be attained. As the utilization of self-contained diving apparatus in oceanographic research continues to expand, many contributions of value will undoubtedly be made, not only through simple observation but also through observation supplemented by the use of instruments and collecting gear carried by the diver. In particular, but not exclusively, we may hope for a more thorough understanding of the rapidly changing, relatively small-scale processes that characterize near-shore waters and are receiving an increasing share of attention from oceanographers.

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7 January 1955.

Extrait

UNION INTERNATIONALE DES SCIENCES BIOLOGIQUES
Série B, No. 16, 1954.

THE DISTRIBUTION OF MACROURIDS

By Carl L. Hubbs (La Jolla)

The anacanthine (gadiform) fishes of the family Macrouridae[1]) range around the world, from the equator to the polar seas. Most of the many species live on the continental slopes, a few on the abyssal ocean floor, a few, toward the poles, on the continental shelf. They are typically benthic, though some and perhaps all are pelagic or bathypelagic during early stages. A few species, including the members of the recently named genus *Phalacromacrurus*, which Scripps Institution has taken off Baja California, appear to be bathypelagic throughout life.

In both species and individuals, the macrourids have commonly been regarded as the most numerous of deep-sea fishes. This conclusion seems to hold for certain regions, notably the Philippine and adjacent seas, but definitely not for other regions, such as western North America, where there are very few species of macrourids, but many deep-sea members of other families, particularly the Liparididae. For the deep seas of the world as a whole, the family Macrouridae is probably the most speciose, though it is exceeded by the Brotulidae in number of recognized genera (a subjective evaluation). The genera of macrourids seem, as a rule, to be widespread.

On critical study most macrourid species appear to be as sharply limited in distribution as are the shore fishes. Very few are common to any two of the following regions: Europe, western tropical Atlantic, Panamá, California, Japan, Hawaiian Islands, Philippine Islands, East Indies, and the subantarctic regions. The sharp distinctions between the species lists determined by Gilbert and Hubbs for the Philippine Islands, southern Japan, and the Hawaiian Islands indicate for the Macrouridae a sharper subdivision of the Indo-Pacific fauna than is exhibited by many of the groups of littoral fishes.

The distribution of the benthic bathybial fish species, in the Macrouridae and in other families, is probably limited less by the very slight regional differences in life conditions in the depths than by the trenchant distinctions in the temperatures and other environmental parameters of the superficial waters inhabited by the young stages. The pelagic stages, therefore, seem to be more effective in limiting than in widely expanding the distribution of the species.

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[1]) The family name Macrouridae, in this spelling, may now be validated (in accordance with nomenclatorial decisions reached just before and during this Congress), whether or not *Macrourus* be synonymized with *Coryphaenoides*.

Careful studies by Gilbert and Hubbs of the large series of macrourids collected by the American "Albatross" in Japan in 1906 and in the Philippine Islands in 1907–10, with supplementary examinations of material from other regions, revealed in these deep-sea fishes patterns of distribution and speciation similar to those determined for fishes of shallow water. For example, the few species of northern Japan range widely around the North Pacific, whereas the species of southern Japan are related most intimately with those of the Philippine Islands. Some close relationships are apparent between the Philippine macrourids and those of the Hawaiian Islands and with those of India. Many types are confined largely or wholly to the Indo-Pacific region, which is outstandingly rich in macrourids. Differentiation was demonstrated for *Hymenocephalus* on the level of localized, intergrading subspecies. Isolation appears to have been a major factor in the speciation of the group, particularly in the Sulu Sea depression, where isolation has been accompanied by uniform and moderate temperatures below the sill and probably by other distinctive features of the physical and biotic environment.

Discussion:

T. Gislén: I draw the attention to the fact that the depths of the Sulu Sea, as evidenced by the Galathea Expedition, are deficient in oxygen. This concerns especially the benthic where the amount of organic refuse, coconuts, nipa palm nuts, etc. is very rich. Now it is the question how high up in the water this deficiency layer of oxygen will expand.

Carl L. Hubbs: I am familiar with the reduced content of dissolved oxygen below the sill of the Sulu Sea but cannot tell what effect this may have on the distribution and speciation of Macrourids. The specimens from the depths of the Sulu Sea were heavily parasitized, perhaps because of the stagnant water; but I agree with Dr. Gislén's suggestion that the low oxygen content may have been a factor in such disease, as it is in polluted waters.

Talbot H. Waterman: One matter of considerable interest concerning the Macrouroids is the presence in many species of large well-developed eyes. These have highly organized retinas and corresponding large visual centres in the brain. Such well-developed visual systems suggest that this sense plays an important part in the behaviour of these fishes; although they live in regions which are absolutely dark as far as sunlight is concerned. Such highly developed eyes might seem to contradict the earlier generalisations of Chun, Brauer, and Murray and Hjort. They observed in general both in the fishes and in the crustaceans that as the intensity of sunlight grows less the eyes of many forms tend to become larger down to the twilight zone between 500–1000 meters. Below this level reduction of the eyes and visual centers is usually evident as in the case of the Ceratioids which mainly live as adults below 1000 m. Yet in the bottom living Macrouroids from much deeper levels well-developed eyes are common. Do you have any comments to make on this situation?

Carl L. Hubbs: The retention of well-developed eyes in such deep-sea fishes as Macrourids may be related to the bioluminescence of the fishes of this family and of associated animals—as in the association of the sexes or in the finding food. In some genera, as *Bathygadus*, and *Hymenocephalus*, the species from the greater depths have bones, large sensory cavities and eyes of reduced size.

BIANCO LUNO A/S, KBH.

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CALIFORNIA FISH and GAME

"CONSERVATION OF WILDLIFE THROUGH EDUCATION"

VOLUME 41 JANUARY, 1955 NUMBER 1

SEPARATION OF EGGS OF SYNENTOGNATH AND ALLOTRIOGNATH FISHES IN EARLY EMBRYONIC STAGES[1]

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The large, often pink or amber, eggs of allotriognath fishes (especially of the ribbonfishes, *Trachipterus* spp.) are occasionally taken in plankton samples in California waters. When these distinctive eggs are in advanced stages of development they are readily recognized as allotriognaths by the peculiar morphological characters of the embryo. In early developmental stages, however, these eggs can readily be confused with pelagic eggs of certain eastern Pacific synentognath fishes, especially the flyingfishes of the genus *Exocoetus*. Since *Exocoetus* sp. has been taken at least as far north as the Revillagigedo Islands, this genus is a part of the fauna with which California ichthyologists are concerned, and it is therefore desirable to record some basic differences in embryonic characters by means of which early stages of its eggs and those of allotriognath fishes can be distinguished.

Most of the described eggs of synentognath fishes bear filaments on the capsule, and are attached rather than free-floating (see especially Hubbs and Kampa, 1946). Such eggs are readily distinguished from those of the allotriognaths, for the latter have no filaments. Bruun (1935) found, however, that ovarian eggs of *Exocoetus volitans* and *E. obtusirostris* in the Atlantic are entirely devoid of filaments, and he suggested that they would prove to be pelagic. This is amply substantiated by material that is now available. Plankton samples taken on the ''Shellback'' cruise of Scripps Institution in the eastern Pacific in 1952 include eggs that are readily identified as *Exocoetus*. Many of them contain advanced embryos, some of them near hatching stage. Two species of *Exocoetus* are known to occur in the eastern Pacific (*volitans* and a form near *obtusirostris*). Whether the eggs in our collection are referable to more than one species has not yet been determined, but for the purposes of this paper it is adequate to treat these eggs simply as *Exocoetus* sp.

Eggs of allotriognath fishes are relatively large. Those that I have examined have a diameter of 2.5 to 3.0 mm. The transparent but commonly discolored (pink or amber) capsule is, in most of them, smooth and non-textured or is more or less striated. Eggs from the Mediterranean that Sanzo (1940) identified as *Lophotes* [=*Lophotus*] *cepedianus*, on the basis of the larvae that hatched from them, had a very finely sculptured capsule.

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[1] Submitted for publication August, 1954. Contributions from the Scripps Institution of Oceanography, New Series, No. 766.

The eggs of *Exocoetus* sp. from the "Shellback" expedition collections have a diameter of about 3 mm. The capsule is smooth and transparent, colorless or faintly pink, and completely lacks filaments, spines, or other modifications. Superficially, these eggs are therefore essentially similar to those of most known allotriognaths.

In early stages the embryos of *Exocoetus* and those of allotriognaths are much alike, especially in the large yolk sac, the absence of an oil globule, the proportions of the large bulging head and the long narrow body axis, the long gut that extends well back beyond the surface of the yolk sac, and the rather early development of the pectoral fin buds. In these early stages there are, however, already some distinct differences that forecast the great divergence of these two groups of fishes in their later embryonic development. In the allotriognath embryo the heart is in the typical chordate position, under the neck, and it remains in that position throughout embryonic development; in the synentognath embryo the heart is displaced forward onto the front of the yolk sac. In the allotriognath the tail tip remains in the simple, straight, embryonic condition; in the early synentognath embryo the tip of the notochordal axis enlarges and bends upward, the fin fold widens around it, and the definitive hypural and ray elements become large and well defined long before hatching. Allotriognath fishes, insofar as their early stages are known, are remarkable for the extreme elongation of one or more of the anterior dorsal rays in the advanced embryonic stages and in the larvae. This specialization is presaged in the early embryo by the precocious formation of a small knob-like enlargement on the mid-dorsal line in or slightly anterior to the pectoral region. No such structure develops in synentognath embryos.

These characters, summarized in Figure 1, should help to distinguish early embryos of these two orders of fishes, whether taken in plankton samples or from stomach contents.

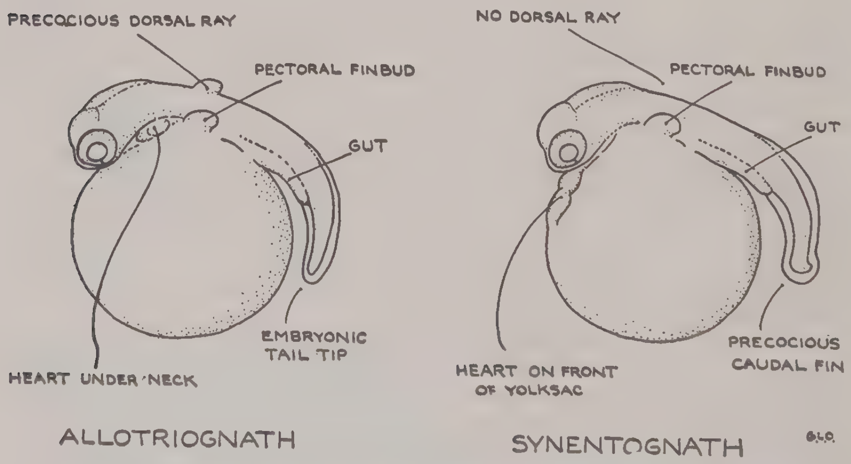

FIGURE 1. Diagrams of early embryonic characters of allotriognath and synentognath fishes (egg capsules and pigmentation omitted)

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11330 1-55 250
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The Return of the Gray Whale

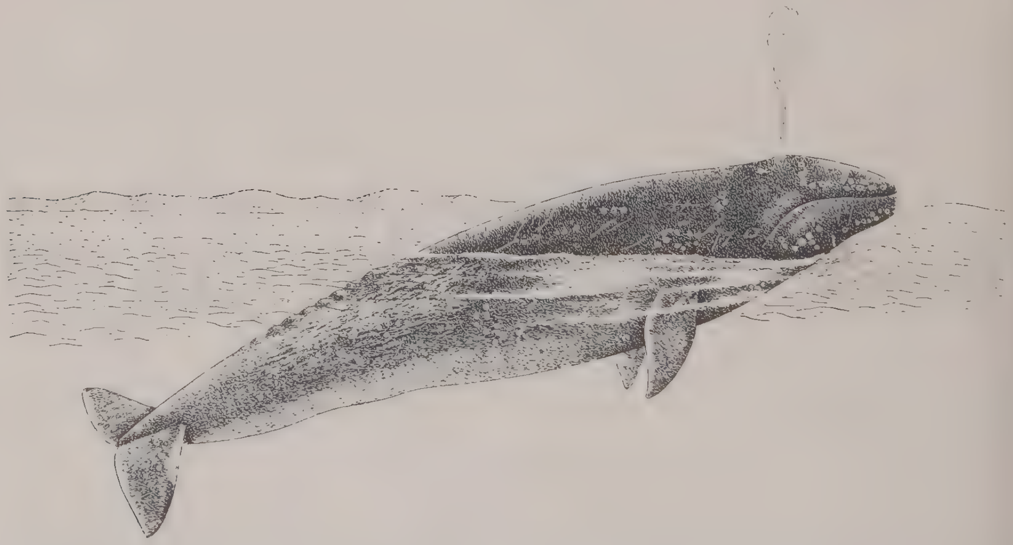
All winter long these smallish whales parade down the Pacific Coast to their breeding grounds. They have twice come back from the brink of extinction, which presents several interesting biological questions

by Raymond M. Gilmore

Contribution of the Scripps Institution of Oceanography, University of California
New Series, No. 767

On almost any clear weekend day this winter, hundreds of people will gather on the high summit of Point Loma over San Diego Bay to watch a rare sight. What they see is a succession of small puffs of vapor spurting from the sea, the rounded line of a long, dark back, perhaps the flirt of a sharp, black butterfly-tail. These signs mark the passage of a gray whale. Nowhere else in the world can city dwellers see at their doorstep a natural spectacle such as the Public Whale Watch at San Diego sponsored by the National Park Service. All winter long, from late December through February, the gray whales parade by in a long line, a mile or so offshore. They are coming home to breed, after a journey of 12,000 miles or more to their Arctic summer feeding grounds and back.

Twice almost exterminated by man, the gray whale is back by the thousands again. If it is an object of fascination to the spectators on Point Loma, it is no less so to marine biologists and conservationists. How did the gray whale survive and rebound to such numbers, after being reduced by whalers to a population of probably no more than 100 only 20 years ago? Why does it make its tremendously long spring migration to the Arctic, when there seems to be plenty of food in its mating grounds off Lower California—or why does it come back each breeding season, when a relative,



GRAY WHALE (*Rhachianectes glaucus*) is about 40 feet long. The color of its mottled skin ranges from very light gray to almost black. It feeds on plankton by filtering water through blades of whalebone or baleen hanging down from each side of its upper jaw.

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the Arctic right whale, stays in the North? Will the gray whale population continue to multiply, now that it is protected from hunters by international law? Students of the species have recently looked into some of these questions closely, even to taking censuses of the gray whales from the shore and from the air by plane and helicopter.

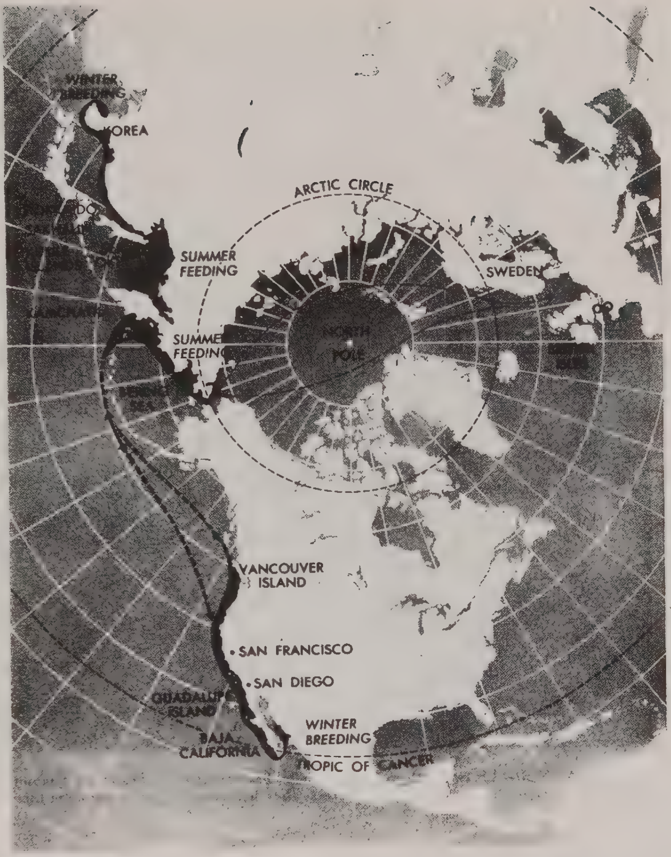
The gray whales concentrate their reproduction each spring in certain bays and lagoons of northwestern Mexico. One of the peculiarities of the creatures is that they mate and calve only within those few retreats. Their long-range survival therefore seems somewhat in doubt, since a fall of only a few feet in the sea level, drying up their breeding places, might wipe out the species unless it changed its breeding habits.

The gray whale is a moderate-sized cetacean about 40 feet long—considerably smaller than the giant blue and finback species. It is a hardy animal, as its long, difficult yearly travels testify. All summer the gray whale lives in the polar waters off Kamchatka and the Bering Straits. There it fattens on the abundant large plankton, especially euphausiid shrimps. When the days shorten and late autumn's cold settles down, the whales set off for the Mexican waters some 6,000 to 7,000 miles away. As to why they make this tremendous journey, we can find no answer better than that their inherited habits must be stronger than the environment.

The whales push through storm and calm across the vast northern Pacific toward the North American coast, wasting little time to feed in transit. This part of their trip has never been observed by man. Their route is figured out simply by putting together the two ends of the puzzle: gray whales disappear from the Bering Sea and as mysteriously reappear off the North American coast. They hit the coast at Oregon and northern California and thereafter hug it closely all the way down to Mexico, probing the shoreline for the entrances to their accustomed breeding lagoons.

Just why they come in near the coast so far north of their destination is a question. Their route follows almost exactly a great circle course from the Aleutians; perhaps they are accurate navigators. On the other hand, it is possible that they used to breed along the coast north of their present places in warmer times.

After the gravid females have relieved themselves of their ponderous burdens (a full-term calf is 12 to 14 feet long), and the other females and adult males have performed the vital act of procreation, the gray whales set forth again to the Arctic in March and April. They have taken almost no rest, and are much thinner than when they arrived. On the way north along the coast they scatter more widely than on the way down, because they are no longer searching the coast for their havens. But many rendezvous in a great mass off Vancouver Island before they disappear into the northern Pacific.



DISTRIBUTION of the gray whale is outlined in dark blue on this map. There are two separate populations of gray whales: the Korea population and the California population. The latter migrates (*heavy dotted lines*) between the Bering Straits area, where it feeds, and Lower California, where it breeds. Remains of gray whales (*small circles*) have been found in Europe, suggesting that at one time some migrated across the Arctic (*light dotted lines*).

One might suppose that the arduous annual migration would be a weak link in the life cycle of the species—that many would fall by the wayside. But there is no evidence of any high mortality during the gray whale's journeys. A much more vulnerable part of its cycle is its dense yearly concentration—almost unparalleled among whales—along the California and Lower (Baja) California coasts. In the late 19th century men in whaleboats slaughtered the gray whale in its calving lagoons and its narrow coastal migration path. Again in the 1920s and 1930s, when the herd had begun to come back, it was all but destroyed, this time more efficiently, by whaling factory-ships shooting explosive harpoons from cannon.

From an estimated population of more than 25,000 in 1840 the herd was reduced to perhaps about 100 by the late 1930s. In its current comeback it now numbers some 3,000 and is increasing. For the present the species seems safe,

THREE GRAY WHALES, two of them emitting their characteristic puffs of vapor, were photographed by Gilmore as they fled across Scammon Lagoon on the Pacific coast of Lower California. He was pursuing them in a rowboat propelled by an outboard motor.

FLUKES of a gray whale flip into the air off La Jolla, Calif. They are encrusted with barnacles and actually overgrown with kelp.

HEAD of a gray whale bobs out of the water as it peers curiously at a rowboat in Scammon Lagoon. The lower jaw is to the left.

thanks to the prohibition against hunting it and to its secure havens in the sheltered lagoons that fringe the uninhabited deserts of Lower California. But its situation remains fundamentally precarious. Its breeding lagoons are smaller than they once were; some of them today are salty wastelands left by the receding water to dry in the burning sun. Moreover, the whales have been driven from three of its largest bays by heavy boat traffic. Indeed, the gray whale is a relict species in a shrinking environment.

The species might well survive, however, even if it were pushed out of its shelters. Newborn calves have been seen outside the lagoons, suggesting that they were born in the open sea, and the members of a small isolated herd of gray whales off Korea are known to calve in unsheltered waters.

Right now we are attempting to find out how many gray whales there are, and to project a curve of probable population growth into the future. There are two censuses, one from the air and the other from land. They were started by Gifford C. Ewing and Carl Hubbs of the Scripps Institution of Oceanography, and have been carried on by the cooperating Fish and Wildlife Service. The air census counts all the adults and calves visible on the water's surface over the entire breeding range; the land census counts the adults in the migration procession as they pass Point Loma and the Scripps Institution at La Jolla 10 miles to the north. It is estimated that the censuses catch from one third to one half of the total population.

The two counting methods have given surprisingly close results. The count in 1953 was 1,156, including 190 calves; in 1954 it came to 1,200 adults and 200 calves. Allowing for those missed, it is estimated that the total population numbers between 2,500 and 3,000.

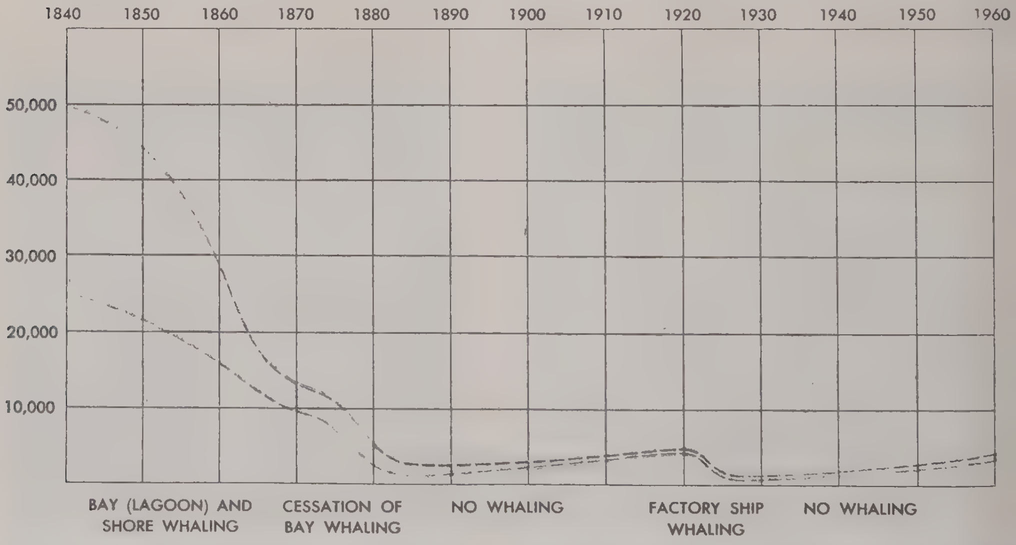
Where does this figure fit into a growth curve of the population? We have two earlier points of reference: a high point of more than 25,000 in the mid-19th century and a low point of perhaps 100 in the 1930s. In its recovery from the low point the population will probably follow the classical "logistic" or Verhulst-Pearl curve of population growth, which was derived from studies of laboratory cultures and of human populations. This is a smooth S-curve, starting with a slow rise, then climbing steeply and finally leveling off after a saturation point is reached.

The present breeding grounds of the gray whale could accommodate a population of about 25,000. It is not likely, however, that its numbers will ever at-

MALE AND FEMALE whales were photographed by Gilmore in Scammon Lagoon as they rolled about in the water before mating. The flukes of the female may be seen at the left. The male is at the right. The females also give birth to their calves in these waters.

tain the saturation level, because in coming decades the demand for the protein food the whale can supply will be too great. We must therefore modify the curve to provide for some whaling [*see chart below*]. It is to be hoped that the annual catch, suitably apportioned among all the interested nations, will be restricted to a level which will assure the perpetuation of the species.

Without much doubt, the North Pacific has always been the heartland of the gray whale. But evidence has recently come to light that herds of the species once lived in the North Atlantic also. Remains of gray whales have been found in Pleistocene or recent deposits in estuaries of Sweden, southern England and the Netherlands. Their presence in estuaries indicates that in ice-age times, as now, the species was accustomed to



DECLINE AND RISE of the gray whale is shown by this curve. The thickness of the curve represents the uncertainty of the population estimate. The population in 1840 is thought to have been at least 25,000. It fell to no more than 100 and is now about 3,000.

(300)

mate and calve in sheltered waters to which it retired in season.

Presumably during interglacial periods, when the Arctic Ocean melted, gray whales spilled over from the Pacific population across the Arctic into the Atlantic. Some cetologists believe that the gray whale survived along our Atlantic seaboard until historic times; one even insists that it still exists there today, though in such small numbers that it has not been discovered. The evidence for its recent presence off this coast depends heavily upon a report in 1725 by one Paul Dudley, who in the *Philosophical Transactions* of London described a New England whale which may have been a gray:

"The Scragg Whale is near in kin to the Finback, but instead of a Fin upon his Back, the Ridge of the Afterpart of his Back is scragged with half a Dozen Knobs or Nuckles; he is nearest the Right Whale in Figure and for Quantity of Oil, his Bone (baleen) is white, but won't split."

The Dutch authorities A. D. Diense and G. C. A. Yunge are convinced that the New England "scragg" was a gray whale. But it seems more probable that the scragg was merely an undersized right whale; the early New England whalers applied the name scragg to any runty right or humpback whale. William Schevill of the Woods Hole Oceanographic Institution has described Dudley's report as a "literary curiosity." I would not be surprised to see fossil remains of gray whales come to light on the New England or Canadian coast, but I doubt that man has ever laid eyes on a living member of the species in that region of the world.

Why did the gray die out in the Atlantic? Some drastic change in conditions must have done it in completely, for the species has shown in the Pacific a remarkable capacity to come back from extremely low numbers. The whale is not a very rapid breeder, as the animal kingdom goes. In its lifetime of 15 to 20 years a female gray whale may deliver from five to eight young, since it normally calves every second year after maturity. What may stand greatly in the species' favor is its inborn habit of herding each year in the intimacy of its few traditional lagoons—which assures that boy will meet girl, however scarce they may be.

The mighty drama of the gray whale's comeback, a drama which we are witnessing from excellent seats on the California coast, is a moving sight. Let us hope that it will have a happy ending.

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(mailed May 26, 1955)

RECORDS OF *KOGIA BREVICEPS* FROM TEXAS, WITH REMARKS ON MOVEMENTS AND DISTRIBUTION

By Gordon Gunter, Carl L. Hubbs, and M. Allan Beal

Kogia breviceps (Blainville), the pygmy sperm whale, has been recorded repeatedly from the Atlantic Coast of North America (Hobbs, 1885; True, 1885; Allen, 1941, and papers cited therein; Ulmer, 1941; Enders, 1942; Brimley, 1946; Moore, 1953), but to date the only published report from the Gulf of Mexico is that of Moore (1953: 129), based on an adult that washed ashore in November, 1949, on St. Petersburg Beach, Pinellas County, Florida, and there gave birth to a calf.

First specimen from Texas.—Almost a year earlier, on December 27, 1948, another adult female (Pl. I, Upper and Middle) was stranded near the north end of Mustang Island, Nueces County, Texas, a mile south of the Aransas Pass jetties. It was examined while fresh (with blood draining from its mouth) by staff members of the Institute of Marine Science, in the absence of the first author. Photographs were taken and the head was buried on the Institute grounds, but these circumstances were not reported, because the specimen was thought to be a blackfish. The photographs were later shown to Raymond M. Gilmore, who saw that they represented the rare pygmy sperm whale, and to Hubbs, after the second specimen had come to light in Texas. Information on the buried head enabled Gunter to disinter the skull (Pl. II), minus the teeth and the lower jaw.

Certain differences seem to be indicated when the proportional measurements of the Mustang Island specimen (Table 1) are compared (Table 2) with those of Hubbs (1951: 507), for a California specimen, and of Enders (1942, Fig. 2) for a New Jersey specimen. Not many measurements are similar, because standardized criteria have not yet been developed, but seven measurements were the same or can be estimated with reasonable accuracy. The proportional width of the flukes was much the same in the California and New Jersey whales, and much less in the Texas specimen. However, it seems that the Texas carcass was twisted and that the flukes were not completely spread when measured. The flipper in the Texas animal (a female) seems to have been considerably larger, proportionally, than in the other two (both males), and since this indicated difference appears to be borne out by the photographs, the difference is probably real, but whether sexual or not remains to be seen. The length of the dorsal fin and its vertical height were much the smallest in the New Jersey specimen and this indication is apparently confirmed by a comparison of the three photographs and of Enders'

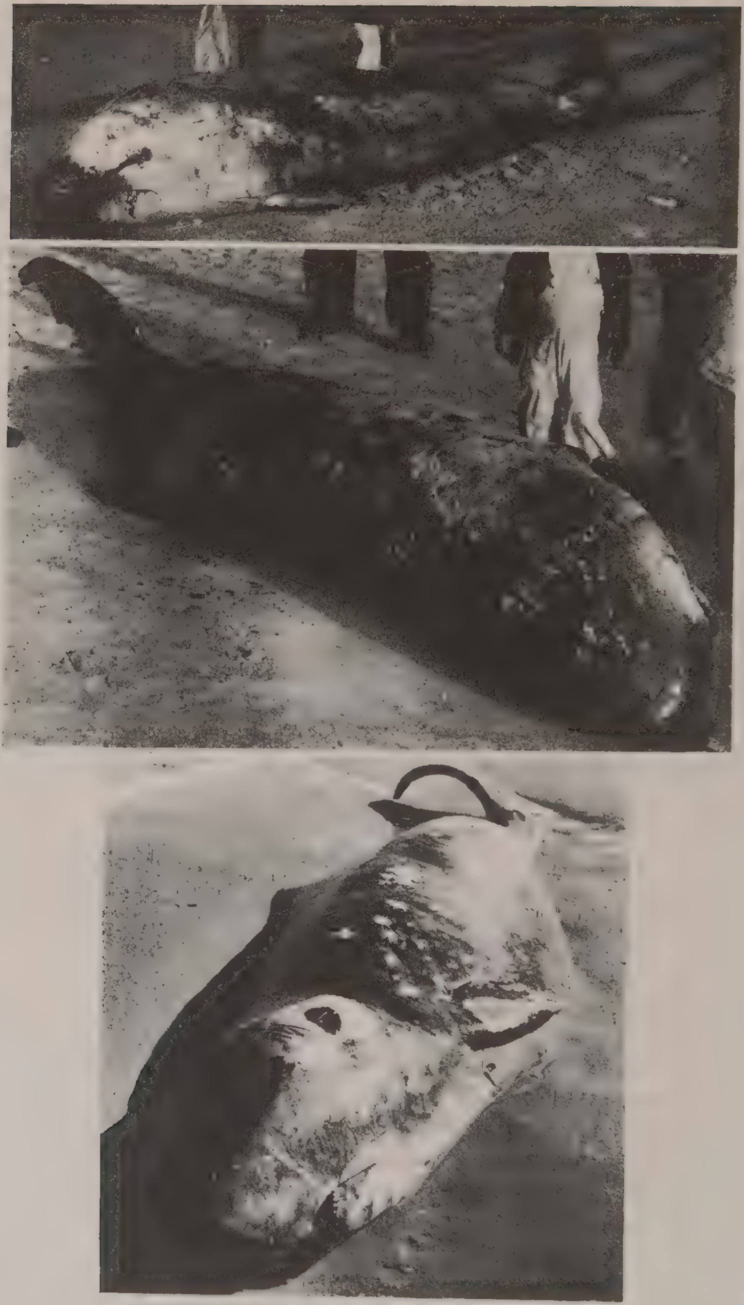

PLATE I

Upper and Middle: Pygmy sperm whale stranded at Mustang Island, Texas, December 27, 1948. Photographs by David Kramer.

Lower: Pygmy sperm whale stranded at Padre Island, Texas, February 7, 1954. Photograph by M. Allan Beal.

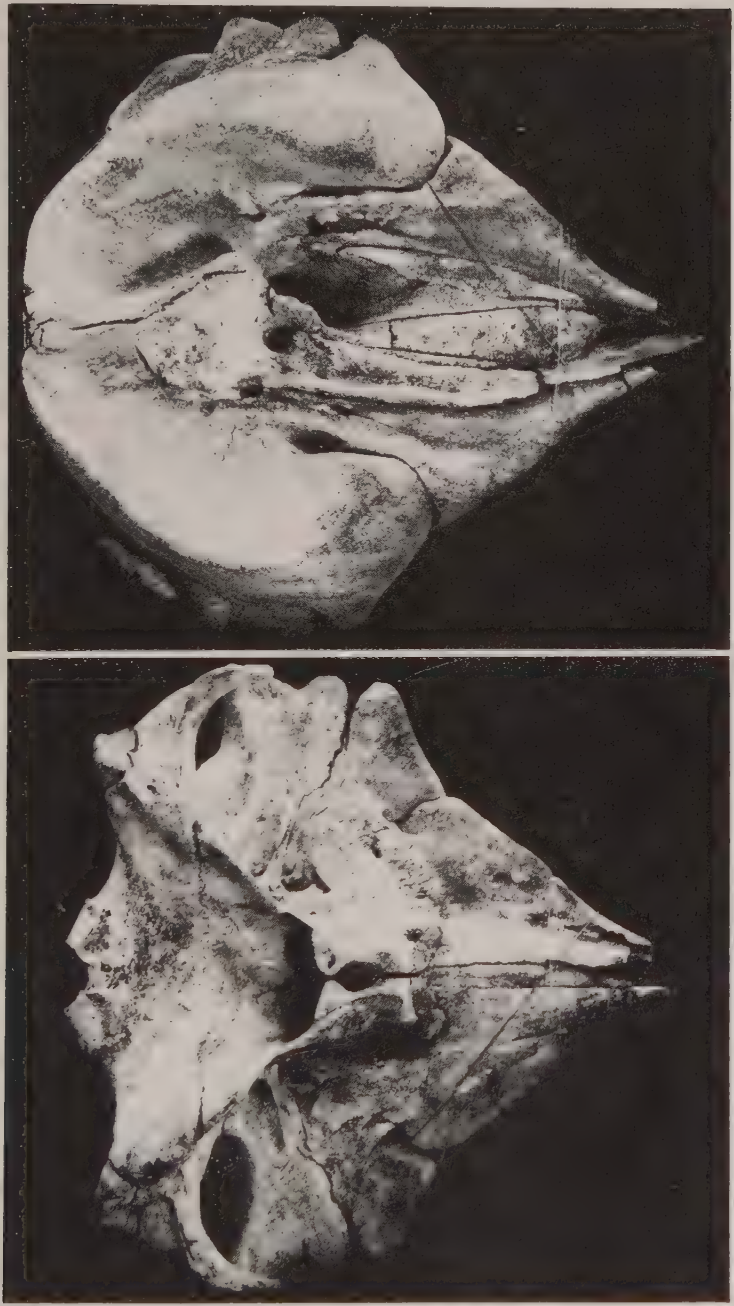

PLATE II

Skull of pygmy sperm whale stranded at Mustang Island, Texas, December 27, 1948. Dorsal view above, ventral below. Photographs by Jack Blackwell.

TABLE 1.—*Measurements of the Mustang Island specimen of Kogia breviceps*

Measurements of the carcass, by Joel W. Hedgpeth, December 28, 1948

	Inches	Thousandths
Total length, to notch in flukes	108	1,000
Width of flukes	20	185
Length of left flipper	19–20	176–185
Dorsal fin height	5	46
Dorsal fin length	16	148
Snout tip to rear of dorsal base	75	694
Snout tip to blowhole	14	130
Snout tip to eye	16	148
Notch in flukes to rear of dorsal base	36	333
Notch in flukes to flipper base	78	722
Body depth at base of dorsal	25	231
Greatest body depth*	28	259

Measurements of the skull, by Gordon Gunter, July, 1954

	mm.	Thousandths
Condylobasal length	443	1,000
Zygomatic width	395	892
Supraorbital width	406	916
Rostrum length	221	499
Braincase height	181	409
Braincase length	133	300

* About two-thirds of distance from tip to snout to posterior end of dorsal fin.

TABLE 2.—*Comparative measurements* of California, Texas, and New Jersey specimens of Kogia breviceps*

	California (male)	Texas (female)	New Jersey (male)
Flipper length	134	176	137
Dorsal fin height	66	46	31
Dorsal fin length	147	148	(60)
Snout to front of dorsal	499	(600)	516
Rear of dorsal base to fluke notch	(418)	333	436
Snout to blowhole	116	130	107
Snout to eye	156	148	110
Fluke width	242	185**	248

* The measurements are expressed in thousandths of length from tip of snout to notch between flukes of each animal. Estimates are in parentheses.

** Fluke probably not fully spread.

diagrammatic drawing of his specimen. The length of this fin was much the same in the California and Texas specimens (male and female, respectively).

The most unexpected and significant differences seem to be the measurements of snout to eye, snout to blowhole, and snout to dorsal fin. The last measurement is checked by the measurement from the fluke notch to the posterior insertion of the dorsal. These measurements and a comparison of the photographs indicate, with little doubt, that the dorsal fin of the Texas specimen was placed considerably farther back than on the other two. The blowhole of the Texas specimen seems to have been more posteriorly placed than in the other two. The eye was considerably posterior to the blowhole in both the Texas and California animals, but Enders' diagram and measurements indicate that the eye of the New Jersey whale was only a little behind a vertical line through the blowhole. These seem not to be sexual differences, for the Texas specimen was a female and the other two were males.

Thus it appears that the body proportions of the pygmy sperm whale adults may vary considerably. The flipper may be much larger in some than in others. The dorsal fin may vary considerably in size and it may be placed much more posteriorly in some than in others. The eye may be almost vertically in line with the blowhole or considerably behind it.

None of the photographs of the Texas specimens shows the bracket-like mark figured and described by Hubbs as extending in the California example from near the ear to a point in front of the flipper, but such markings in cetaceans fade rapidly on death, particularly in specimens that have been rolled in the surf and then exposed to the sun. The information from Charles L. Camp, reported by Hubbs, shows that the mark is developed on at least some Atlantic specimens. Yamada (1954) has shown that a similar mark, with variations, occurs on Japanese specimens.

Second specimen from Texas.—The second specimen (Pl. I, Lower) to be recorded from Texas was observed and photographed by Beal on the Gulf beach of Padre Island, about 20 miles south of the latitude of Corpus Christi, on February 7, 1954, while a "norther" was blowing. No measurements were made and no parts were preserved, for the rarity of the find was not then appreciated.

Though the length of the specimen was estimated as only about nine feet, the animal appeared to be old, for its teeth were worn down to broadly rounded pegs, contrasting sharply with the needle-like structures commonly seen in this species (as shown by Hubbs, 1951, Pl. 3). The worn teeth dramatized the small size attained by this whale.

Obviously there is much variation in the size and probably in the age at which odontocetes wear their teeth down to rounded pegs. Among 33 specimens of the bottlenose dolphin, *Tursiops truncatus* (Montague), Gunter (1942: 270) noted one old female, 8.5 feet long, with much worn teeth, although the species reaches a length of 12 feet. A very similar observation has been made by Schevill and Lawrence (1953: 152). Blunt-toothed adults of *Tursiops gilli* Dall, of moderate length, have been seen by Hubbs. Similar though hardly such extreme age variation has been observed in the teeth of sperm whales, *Physeter catodon* Linnaeus; for example, by Hubbs, at the Field's Landing whaling station in California.

Movements and distribution.—The fact that both Texas specimens were taken in the winter prompts a consideration of the seasonal occurrence of pygmy sperm whales in the western North Atlantic. When the 31 available dated records are tallied (Table 3) there is to be noted a complete lack of records for the months of June, July, and August, and only two records for May (May 7 and 19). Since in these months the beaches are commonly frequented, it seems highly probable that the major population of the species in the western North Atlantic is then centered somewhere outside or beyond the inshore waters of the Atlantic Coast

TABLE 3.—*Records of the pygmy sperm whale along the western coast of the North Atlantic Ocean, arranged by six-degree bands of latitude*

Latitude	Month											
	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
26°–32°	1	1		1					3*		2	1
32°–38°		2		3**	2				1		1	2†
38°–44°	1	2	2	2						3‡	1	
Totals	2	5	2	6	2				4	3	4	3

Summary	January to May	June to August	September to December
26°–32°	3	0	6
32°–38°	7	0	4
38°–44°	7	0	4

* Including a calf with one of the two adults.

** Two of these were suspected of being a cow and an accompanying yearling.

† One of these specimens was reported by Allen (1941: 20) to have been stranded in January, but the original accounts of this specimen, by True (1885) and by Hobbs (1885), indicate the month as December.

‡ Two of these were suspected of being a mated pair.

from 26° to 44° N. Lat. There is at least a suggestion of a northward movement between fall and spring. It is quite possible that the pygmy sperm whale, like some of the larger cetaceans, moves rather far toward the poles, in the summer, to feed on the rich pelagic food supply of those regions, returning to warmer waters to breed.

Table 3 includes four hitherto unpublished records from South Carolina, supplied by the Charleston Museum, as follows: (1) male 10 feet, 1.5 inches long, stranded on Pawley's Island, Georgetown County, November 15, 1929 (No. 29.264); (2) male 6.5 feet long, with teeth not yet out of gums, reported harried and driven ashore by porpoises, on Isle of Palms, Charleston County, February 3, 1931 (No. 31.27); (3) male 10.5 feet long, stranded on Sullivan's Island, Charleston County, September 12, 1934 (No. 34.289); (4) adult specimen stranded on Seabrook's Beach, Charleston County, found in badly decomposed condition May 19, 1953, and photographed.

The seasonal distribution of the pygmy sperm whale is somewhat different from that of its large cousin, *Physeter catodon* Linnaeus. The whaling records compiled by Townsend (1935) show that the sperm whale was captured in the Caribbean Sea from February to May, in the Gulf of Mexico from March to July, and off the Atlantic Coast of the United States predominantly from April to November. These data indicate a northward drift from spring to fall. In the winter, it is thought, most of the sperm whales moved southward beyond the equator.

The relative frequency of records from temperate eastern North America and the lack of any from the western Atlantic south of the Gulf of Mexico might be taken as an indication that the pygmy sperm whale is one of the numerous tribe

(Hubbs, 1952) of more or less antitropical organisms. On the other hand, the southward decline in the number of naturalists may explain the lack of southerly records in the western Atlantic. Hirasaka (1937: 138) listed six specimens from tropical Pacific waters. Tropical Atlantic specimens are to be expected.

A curious anomaly concerning the distribution of the pygmy sperm whale seems to be coming to light. The distributional map of Hirasaka (1937) shows that 23 strandings are recorded for the western Atlantic and western Pacific and only eight from the eastern shores of these oceans. Later records (in papers cited in the introduction) have increased this disporportion. The complete lack of records from Great Britain, where strandings of cetaceans are better recorded than elsewhere, is not very significant with regard to total distribution, for there are a few records from France and Holland, but the paucity of records from northern Europe is probably significant, especially when considered in connection with the scarcity of records from western North America.

For several reasons, however, we must be guarded in our conclusions regarding the distribution of the pygmy sperm whale. The records are still too few for statistical reliability. Many strandings go unreported, or the specimens are mistaken for more common species (the two seen on the Gulf coast in 1948 and 1949 were thought to be blackfish, until brought to the attention of a cetologist). The preponderance of winter records may be due to strandings by storms, which are commonest at that season. The paucity of reports from tropical waters may be attributable, in part at least, to the limited number of marine biologists in those regions. We venture the distributional discussion, however, in the hope of encouraging the accumulation of more data on this interesting little whale and of stimulating further thought on its distribution and ecology.

In connection with the distributional analysis it should not be forgotten that some authors have recognized more than one species of *Kogia*, which, if they exist, may have different ranges. On the basis of newly acquired Japanese specimens, Yamada (1954) has considered the problem, without coming to a definite conclusion.

Acknowledgments.—We are grateful to several colleagues. David Kramer made available photographs of the first Texas specimen. Joel W. Hedgpeth provided measurements of this specimen and other information regarding it. Joseph Curtis Moore suggested the tabular treatment of the western North Atlantic records and otherwise commented helpfully on an early draft of this paper. Raymond M. Gilmore, who first identified the photographs of the Mustang Island specimen, has kindly withdrawn in our favor his plan to publish the record. E. Milby Burton and Albert Schwartz kindly made available records of specimens from South Carolina.

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Institute of Marine Science, The University of Texas, Port Aransas; and *Scripps Institution of Oceanography, University of California, La Jolla. Received August 8, 1954.*

[Contributions from the Institute of Marine Science, and from the Scripps Institution of Oceanography (New Series, No. 768).]

A Study of the Structure, Affinities, and Distribution of *Tetraplatia volitans* Busch (Coelenterata: Hydrozoa: Pteromedusae)[1]

CADET HAND[2]

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A Study of the Structure, Affinities, and Distribution of *Tetraplatia volitans* Busch (Coelenterata: Hydrozoa: Pteromedusae)[1]

CADET HAND[2]

INTRODUCTION

THE HYDROZOA include a large number of curious animals, not the least unusual of which are the tetraplatians. Two species of *Tetraplatia* have been described, *T. volitans* Busch (1851) and *T. chuni* Carlgren (1909). These hydromedusans are so highly modified in form that their true nature is seldom recognized when they are first encountered.

Tetraplatians are elongate (to 9.5 mm.) medusans of bipyramidal form with ciliated outer surfaces. The mouth lies at one extremity whereas the other end represents the aboral tip of the bell. In cross section the aboral region may be nearly cylindrical, quadrangular or octagonal while a cross section of the manubrium (oral end) may be circular to quadrangular. A constriction occurs near the middle of the body. In *Tetraplatia volitans* (Fig. 1) this constriction is bridged by flying-buttresses connecting the angular corners of the manubrium to the four major angles of the bell above the groove. These buttresses are absent in *T. chuni*. In the constriction and between the buttresses in *T. volitans*, and in a corresponding position in *T. chuni*, arise four, bilobed, swimming appendages, the wings or lappets. Each lobe of each lappet has a statocyst. These lappets have a solid endodermal core (see Fig. 2). At the free extremity of the lappets there is a thin sheet of ectoderm which is interpreted as the velum; this velar structure may be continuous around the body in the constriction although not all specimens seem to show this. The lappets commonly have been called bilobed; however, at their free end 8 or 10 small velar projections can be found, four or five to each lobe. These projections are the result of at least three bifurcations of the supporting structure within the lappet, the first producing the bilobed appearance of the contracted lappet and the latter ones leading out to the terminal velar projections of the lappets (Fig. 3). The surface of tetraplatians is marked by ridges, which are tracts of nematocysts; commonly the bell has eight tracts, four in the axes of the buttresses and four in the axes of the lappets, although those in the lappet axes may be absent. The manubrium never has more than four rows of nematocysts and these always are in the buttress axes.

Internally tetraplatians consist of a large, essentially quadrangular, gastrovascular cavity. The coelenteron extends into the buttresses from both the oral and aboral halves of the body. It has been reported that at the midpoint of the buttresses there may be a

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[1] Contribution from the Scripps Institution of Oceanography, New Series No. 769. Manuscript received November 22, 1954.

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(312)

mesogleal septum separating the oral coelenteric pouch from the aboral (Carlgren, 1909) or that the passageway may be blocked by an endodermal plug (Dantan, 1925), although neither of these structures is necessarily present.

There are four gonads in the tetraplatians, each with an oral and an aboral bilobed portion. The gonads originate below the velum in the axes of the buttresses and project inside the animal, largely filling the coelenteron when the animal is mature. The sexes are separate.

In summary, the tetraplatians are considered to be tentacleless medusans whose body is divisible into aboral and oral halves, separated by a line of tissue lying in the bottom of a constriction, this tissue representing the margin of the bell and the velum. The subumbrellar part of the animal is highly reduced and consists of only the manubrium and the tissues on the adoral surfaces of the lappets.

REVIEW OF RECORDED KNOWLEDGE

Tetraplatia volitans was first described by Busch (1851), presumably from a single specimen, taken at Málaga, Spain, in the Mediterranean Sea. He apparently observed the animal alive for a period of 2 days, and although he did not express an opinion on the nature or affinities of the animal, his description was good enough to enable subsequent authors to recognize it. Shortly after Busch's discovery, Krohn (1853) reported the finding of four specimens at Messina, Sicily. Twelve years later, having obtained no more specimens, Krohn (1865) published detailed observations on the four specimens he had obtained and suggested they must be young forms of some medusa (scyphozoan). Leuckart (1866), in considering the work of Krohn, suggested that *Tetraplatia* might be related to the medusan group of aeginids (now narcomedusans), and subsequently Claus (1878) in a very fine study established quite definitely the hydromedusan nature of the animal although at the same time he seemed to feel that it was half medusan and half polypoidal and thus intermediate between polyps and medusae. Claus, however, used the name *Tetrapteron* (*Tetraplatia*) *volitans* for this species, and thereby created the first of the two recognized synonyms of *Tetraplatia volitans*, the second being that of Fewkes (1883) who used the name *Tetraptera volitans*. Haeckel (1879) in his "System der Medusen" suggested *Tetraplatia* might be a larval narcomedusan or that it might be intermediate between the hydroid polyps and the craspedote medusae. Fewkes (1883) in a brief note suggested that this curious animal might be best assigned a position between the craspedote medusae and the ctenophores. Viguier (1890), in an elaborate study of *Tetraplatia*, discussed the similarities of this animal to the trachymedusans, hydromedusans, larval actinians, scyphomedusans and ctenophores and seems to favor their relationship to the trachyline medusae. Perhaps the most careful and complete study of the tetraplatians is that of Carlgren (1909) based upon specimens from the Deutsche Tiefsee Expedition and also on specimens from Messina. From a single specimen from the west coast of Africa he described the species *T. chuni*, and after elaborate morphological and histological study of it and of specimens of *T. volitans*, Carlgren proposed a new order, the Pteromedusae, for *Tetraplatia*. This order represented a third group of trachyline medusae of equal rank to the Trachymedusae and Narcomedusae. Subsequent to Carlgren's study Krumbach (1924) decided that the tetraplatians were really larval animals in spite of their possession of well developed gonads, and placed them among the Scyphomedusae. In 1925 Dantan published a detailed study of *Tetraplatia volitans*. He disagreed with Carlgren's study on a number of points, perhaps the most important of which concerned the origin of the statocysts. Dantan maintained that these balance organs were of ectodermal origin, as opposed to the endodermal origin proposed by Carlgren, and after much discussion placed *Tetraplatia* among the Anthomedusae. Weill

(1934) in his study of the nematocysts of the coelenterates concluded from the figures of Viguier (1890) that *Tetraplatia* has a monocnidom of atrichous isorhizas and as such must be assigned to the Narcomedusae. Weill's opinion seems to have been completely accepted by Hyman (1940), and the trachyline affinities of this animal have been quite generally accepted among those who have actually worked with the animal except for Dantan (1925) and Komai (1939). Komai concluded that *Tetraplatia* is a primitive scyphozoan, close to the Cubomedusae and Stauromedusae.

The distribution of *Tetraplatia*, with the data included in the present report, is nearly world wide. The first *Tetraplatia* was taken in the Mediterranean Sea (Busch, 1851) and the next several reports of the animal were also from the Mediterranean concerning specimens taken at Messina. In 1885 Viguier reported finding specimens in the Bay of Algiers and his report of 1890 concerns the finding of these animals at that locality for five successive winters through a seasonal period from the end of December to the last of March and early April. Viguier was the first person to find *Tetraplatia* in large numbers and reported taking 200 specimens in a single net haul. Rose (1926) reported a single specimen from the Bay of Algiers. Carlgren (1909) extended the distribution of *T. volitans* to the neighborhood of the Chagos Islands in the Indian Ocean (4°5.8′ S., 73°24.8′ E.; 2°38.7′ S., 65°59.2′ E.) and also reported the single known specimen of *T. chuni* from the beginning of the Benguela current off the west coast of Africa at 36°23.4′ S., 17°38.1′ E. Dantan (1927) in a brief summary of the distribution of *T. volitans* reported it from the type locality of *T. chuni* but this was apparently an error. The next extension of known range occurred when Leloup (1935) reported the discovery of eight specimens of *T. volitans* from seven net hauls of the "Meteor" samples from the Atlantic (stations 41, 166, 183, 184, 216, 234, 278). These specimens ranged from 17° N. to 29° S. in the eastern Atlantic and

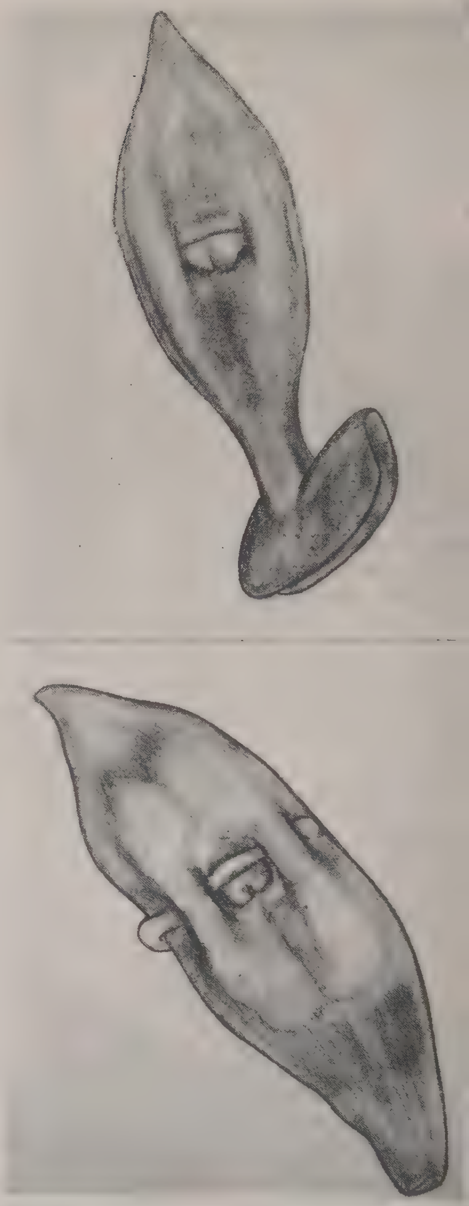

FIG. 1. *Tetraplatia volitans.* The upper specimen shows a widely flaring mouth and presumably was in the process of engulfing food at the time of fixation. (Carbon drawings by Mrs. Lois Stone, Department of Zoology, University of California, Berkeley.)

from about 23° to 30° S. in the western Atlantic (east and south from Rio de Janeiro, Brazil). Komai (1939) reported this animal from the Pacific for the first time. His report concerned four specimens taken in May at Susaki, Japan. Carlgren (personal communication) has informed me that he also has specimens from the western Pacific collected by the Dana expedition. The present report concerns the occurrence of *T. volitans* in the eastern Pacific. A total of 211 specimens has been found in 76 different net hauls from 44° N. to 5° S. and as far west as 131° W. The most northerly specimen was collected at 44° 12′ N., 128° 37′ W.; the most southerly at 5° 04′ S., 95° 56′ W. and the most westerly at 39° 38′ N., 131° 36′ W. Of the total specimens from the Pacific Ocean 167 were collected during the course of routine sampling by the Scripps Institution of Oceanography as part of the California Cooperative Sardine Research Program and also on its expedition "Shellback" to the eastern tropical Pacific. The remaining specimens (44) were collected in Monterey Bay, California, by personnel of Hopkins Marine Station during the course of their work on NC–ONR# 25127. Figure 4 shows the areas from which the specimens from the eastern Pacific were collected whereas Figure 5 indicates the world wide nature of the distribution of *T. volitans*. No specimens have been reported from the Arctic or Antarctic regions, nor as yet from most of the southern and western Pacific.

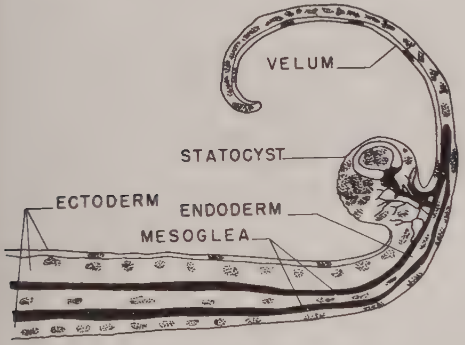

FIG. 2. Section through a lappet and statocyst, oral surface uppermost.

The early workers on *Tetraplatia* commented but little upon its way of life. All the early specimens seem to have been taken in superficial net hauls and usually at night. Viguier (1890) thought they occurred "en petites troupes" and that they were the pelagic phase of a fixed or benthic animal. He points out that he did not find these animals associated with the truly pelagic (oceanic) forms. Carlgren (1909) was of the opinion that the tetraplatians were holoplanktonic. Dantan (1925), however, basing his conclusions on his observations of living animals, their movements and behavior, and on the spotty occurrence of these animals believed that they occur only accidentally in the plankton. He thought that they were not truly pelagic and that they lived near the bottom in rocky areas since net samples near sandy and muddy bottoms did not contain them. Dantan also disagreed with Viguier to the extent that when he (Dantan) found *Tetraplatia* it was in typical plankton assemblages. Leloup (1935) has taken an altogether different point of view on the mode of life of this animal, and one to which I subscribe as will be seen in the observations and discussions to follow. He points out that the animals seem to be taken either in deep hauls during the day or in surface hauls during the night and suggests the animal must undergo a diurnal migration, coming to the

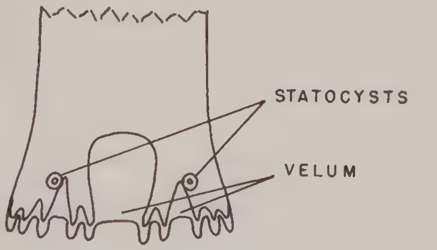

FIG. 3. Oral view of an expanded and flattened lappet.

surface during the night. He also notes that whereas Dantan thought *Tetraplatia* must live near the bottom many specimens have been taken at distances several thousands of meters above the bottom.

As long as *Tetraplatia* was known from only the Mediterranean Sea it was thought of as an animal of rather regular seasonal occurrence. Viguier (1890) found it to occur from December to April and Carlgren (1909) reports that he was informed by letter that the season at Messina was from January to the end of July. The "Valdivia" material from the Indian Ocean was collected in February and March, while the "Meteor" specimens from the Atlantic were collected in March, April, July, October, and November. Carlgren's specimen of *T. chuni* was collected in November. Although the Mediterranean specimens still seem to appear only seasonally this is not true of the Atlantic material, which would appear to be present in all seasons. In the Pacific *Tetraplatia* has been found in samples taken in every month except January and presumably is present at all times of the year. Thus the problem remains of the apparent seasonality of occurrence in the Mediterranean and the apparent lack of seasonality in the Atlantic and Pacific, although samples from the latter two areas are too scanty to rule out seasonal periods of maximal and minimal abundances.

Most of the reports on *Tetraplatia* have dealt with it as a morphologic and systematic curiosity and very little is known of it as a living animal, except for the early studies of Busch, Krohn and Viguier. Dantan (1925) seems to have been the only recent worker to have studied it alive. The foregoing studies, however, give much information on its mode of swimming and the curious writhing movements which it undergoes, and the numerous excellent figures of Viguier (1890) show quite adequately the many shapes this medusa may assume. One interesting fact relative to the living *Tetraplatia* was the report by Viguier (1885) that the refringent bodies (statocysts) were spontaneously luminescent and that they gave off a blue light. In his 1890 report, however, Viguier, after repeatedly seeking to confirm his earlier observation on the luminescence of the statocysts and having failed, suggests that what he observed may have been the result of the beginnings of the decomposition of the statocysts.

OBSERVATIONS ON PACIFIC MATERIAL

The 211 specimens of *Tetraplatia* which have been taken in the eastern Pacific have all been identified as *T. volitans* Busch. These specimens have an average size of 4.2 by 1.6 mm. and a range of from 1.0 by 0.6 mm. to 9.5 by 2.0 mm. The ratio of length to width approaches 1:1 in small contracted specimens although it is about 2:1 in most specimens less than 2.5 mm. long. Specimens of 3 mm. length and longer commonly have a length-

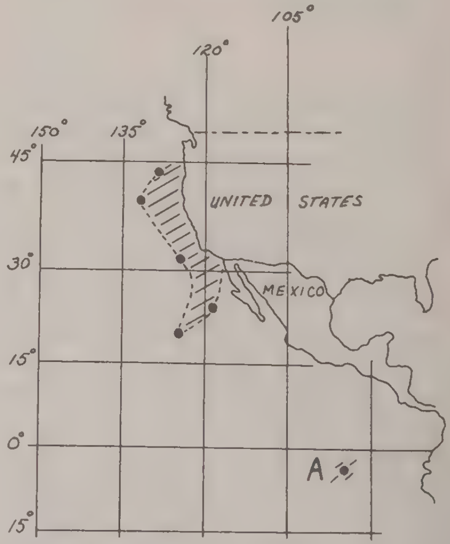

FIG. 4. Distribution of *Tetraplatia* in the eastern Pacific. Shaded area enclosed by dashed line indicates area from which *Tetraplatia* has been collected. The dot at A indicates the position from which the most southerly specimen was obtained, the dots on the dashed line represent the positions of collection of specimens which delimit the area within which most of the material was collected.

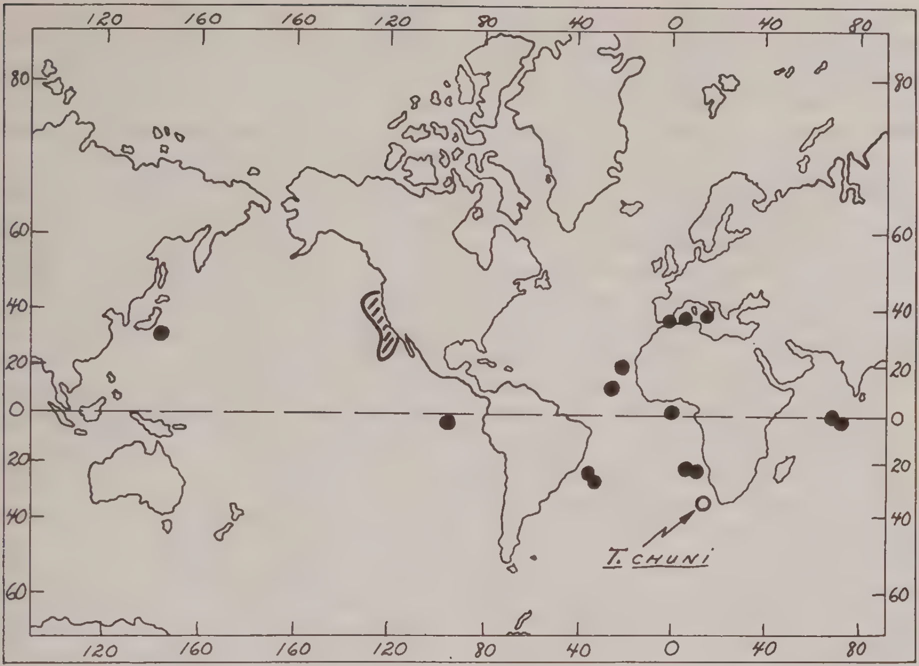

FIG. 5. Worldwide distribution of *Tetraplatia*. Dots and the shaded area in the northeastern Pacific represent localities which have produced *T. volitans*. The open circle is the locality from which *T. chuni* was collected.

to-width ratio of 3:1 with the very slenderest specimens having nearly a 5:1 ratio.

A number of specimens (12) were stained with borax carmine or rose bengal and subsequently cleared. One of the very obvious features of specimens so handled was the absence of the septum in the buttresses. Approximately at the midpoint of the buttresses there may be a slight thickening of the tissues, but in most specimens there was an open endodermal passageway from the oral to aboral coelenteron. In some of the buttresses this passageway seems to be closed off by the endodermal lining, although in six specimens which were prepared as serial sections no blockage was discovered. The passageway is not well formed, however, and consists of an irregular space lined by endoderm and at points along its course the endoderm cells nearly close it off. No sign whatsoever was seen of a mesogleal septum. Komai (1939) also reports the passageway as open, but Dantan and Carlgren, nonetheless, have reported this septum in material they have examined. It would seem therefore that the buttress canals may be closed by a mesogleal septum, an endodermal plug or, more commonly, contain an irregular endodermally lined canal. No special function can be assigned to the buttresses and their contained structures other than the obvious role the endodermal lining must play in the nutrition of the animal.

The presence of these buttresses is the character which most obviously separates *Tetraplatia volitans* from *T. chuni* which lacks these structures. It was therefore of great interest to discover that these structures are not constant and that on some specimens only two buttresses were present. Four specimens were found which represented variations from the normal plan of four buttresses per animal. Figure 6*a* and *b* illustrate the first of these anomalies in which a buttress is nearly separated into halves, the halves apparently connected by only a thin piece of ectoderm. All other buttresses on this specimen were normal. A second anomalous specimen possessed only two buttresses; these were adjacent to one another and were normal in all respects. This specimen, however, possessed only three swimming plates and only the two buttresses just mentioned. Figure 6*c* and *d* illustrates this specimen. This specimen was triangular in cross-section except for the buttress missing from the side shown in Figure 6*d*. A third irregular specimen was one which possessed the normal four lappets but possessed only three buttresses, one being completely missing. The last anomaly was a specimen which also possessed four lappets, but only two buttresses, these being located 180° apart. This specimen is illustrated in Figure 6*e* and *f*.

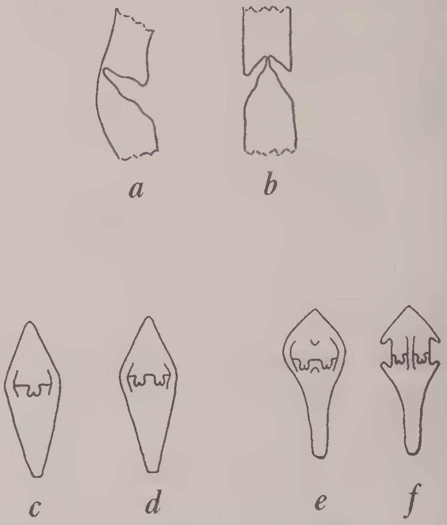

FIG. 6. Some aberrant *Tetraplatia volitans*. *a*, *b*, An incomplete buttress; *c*, *d*, a specimen with three lappets and two buttresses; *e*, *f*, a specimen with four lappets and two complete and two incomplete buttresses.

Carlgren's *T. chuni* seems to be very little different from *T. volitans*, the major differences being the absence of the buttresses and the narrower lappets of his species as compared with *T. volitans*. In *T. volitans* the lappets, in general, are about as broad as the space between any two adjacent lappets, while in *T. chuni* the space between the lappets is about twice as wide as the lappets themselves. Our knowledge of *T. chuni* is based on a single specimen, 8 mm. long by 4 mm. wide, which by the standards of *T. volitans* is an unusually large, robust specimen. Careful measurements on the more robust specimens of *T. volitans* from the Pacific have indicated that the width relationships of the lappets to the space between lappets approaches the relationship of these measurements on *T. chuni*, but no specimen has been found whose lappets are quite as narrow as Carlgren described for his species. Also no specimen of *T. volitans* has been found which was as inflated as *T. chuni* and this in itself may account for the differences observed. In *T. volitans*, as the specimens become greater in diameter (due largely to their state of expansion and contraction at the time of fixation), the width of the lappets becomes less as compared to the space between. It may be, therefore, that the presumed difference in relative widths of lappets between the two species is an artifact of preservation. As far as the difference in presence and absence of the buttresses between these two species is concerned it now is strongly suggested that this difference also may be an artifact, due in this case to a failure in the development of the buttresses. I do not choose, at this time, to synonomize *T. chuni* with *T. volitans*, but such an act does not seem unwarranted. Another matter, which bears on this problem, concerns the geographic position from which *T. chuni* was collected (see Fig. 5). Carlgren's specimen came from the beginning of the Benguela current off the west coast of the tip of Africa, while in the same current, some 14° to the north, Leloup obtained three specimens of *T. volitans* from the "Meteor" samples. From these facts it would not seem unreasonable to suggest again that *T. chuni* may be an aberrant specimen of *T. volitans*.

Among the many plankton samples examined I had the good fortune to discover specimens of *Tetraplatia* in a group of samples from horizontal, closing-net, tows taken in a vertical series. Four series of samples were taken at a single station (approximate position, 33° N., 117° W.) on the 4th and 5th of March, 1953. These consisted of two night series (2000–0330 hrs., 0400–0515 hrs. P.S.T.; the first series of 12 separate tows and the second series of only four separate tows) and two daylight series (1620–1820 hrs., 0615–1100 hrs. P.S.T.; the first of five tows and the second 11 tows). These tows were made with a net 1 meter in diameter, towed for 10 minutes. Table 1 indicates the length of wire used in each of the tows and the numbers of *Tetraplatia volitans* taken.

TABLE 1

THE NUMBER OF *Tetraplatia volitans* TAKEN IN A VERTICAL SERIES OF HORIZONTAL CLOSING-NET TOWS MARCH 4 AND 5, 1953

LENGTH OF WIRE OUT (METERS)	NIGHT SERIES		DAYLIGHT SERIES	
	No. 1	No. 2	No. 1	No. 2
Surface	0	0	0	0
10	0	0	0	0
25	2	0	0	0
40	7	0	0	0
60	4	**	**	0
80	3	**	**	0
100	2	**	*	0
150	0	**	**	0
200	1	**	**	*
300	0	**	**	*
400	..	**	**	*

* Net did not function properly.
** No sample taken.

From the table it can seen that *Tetraplatia* was common in the first night series of samples and was absent from all others. These results agree very well with the suggestion of Leloup (1935) that *Tetraplatia* undergoes a diurnal vertical migration, approaching the surface only at night, except for the absence of specimens from the second night series. Sunrise, on the days when these samples were taken, was at approximately 0625 P.S.T. and during the time when the second series of night samples were taken the moon was slightly more than half illuminated and was nearly overhead. In the first night series no specimens were taken at the surface or at 10 meters depth while two and seven specimens were taken at 25 and 40 meters, respectively, so perhaps *Tetraplatia* was really absent from only the latter two hauls of the second night series. Also, since these latter two hauls were taken one hour and 45 minutes and one hour and 15 minutes, respectively before sunrise, it may well be that the *Tetraplatia* had already begun their descent toward their daytime environment.

Excluding the 19 specimens collected in the series of hauls just reported, a total of 134 specimens has been recovered from 45 net hauls and of the 45 net hauls, only 12 were made during daylight hours. Of these 12 daylight samples, all but one were tows during which the net fished at depths greater than 300 meters, the exception being a tow whose greatest depth fished was approximately 70 meters. As compared to this single daylight haul which captured a single specimen, 15 night net hauls whose greatest depth reached was 70 meters produced a total of 19 specimens. The 11 remaining daylight tows which fished to depths greater than 300 meters produced a total of 79 specimens (1, 1, 1, 1, 2, 3, 7, 11, 16, 17 and 19 specimens per haul, respectively). With the exception of the haul which produced 16 specimens, these hauls were tows which fished from about 500 meters to 1,022 meters. The sample containing 16 specimens was a closing net tow taken at a depth of about 300 meters at 1455 P.S.T. From the data presented above it now seems to be apparent that *Tetraplatia volitans* is a

TABLE 2

THE NUMBER OF *Tetraplatia volitans* TAKEN IN A VERTICAL SERIES OF HORIZONTAL CLOSING-NET TOWS JUNE 12 AND 13, 1952

NIGHT SERIES			DAYLIGHT SERIES		
Wire Out (Meters)	Time	Number of Specimens	Wire Out (Meters)	Time	Number of Specimens
10	2152	0	Surface	0913	0
4	2219	0	10	0935	0
25	2253	0	25	0955	0
40	2400	0	40	1030	0
60	0029	1	80	1130	0
100	0135	1	100	1155	0
150	0205	1	150	1223	0
200	0243	1	200	1300	0
300	0325	1	300*	1340	0
400	0410	4	300	1420	0
			400	1455	16

* Net did not close.

form which undergoes a diurnal vertical migration, approaching the surface at night and returning with the advent of sunrise to rather great depths. It should be pointed out that most of the samples of *Tetraplatia* which have been obtained were collected at positions where the depth to the bottom was greater than 1,000 meters and in many cases in water several thousand meters deep.

The sample mentioned above containing 16 specimens was one of a group of horizontal tows taken in a vertical series on June 12 and 13, 1952 at 33° 28.5′ N. by 117° 46.7′ W. *Tetraplatia volitans* was taken in seven of the 21 tows of this series (six tows of the night series and one of the day series). The results from this series of samples are shown in Table 2.

It will be noticed in this vertical series that by no means all of the specimens were taken near the surface at night, but instead they seem to be fairly evenly distributed over depths of about 40 to 300 meters (assuming a wire angle on these tows of about 45°). In the vertical series reported earlier in this study the center of the population, at night, seemed to have been in the neighborhood of 40 meters. It therefore is apparent that although some tetraplatians undergo a marked vertical migration this is not necessarily the case, although these animals, almost without exception, descend to or stay at depths of 250 meters or more in the daytime.

Little information is available concerning the depths to which *Tetraplatia* may descend. Specimens have been recovered from samples in which the net fished from about 1,000 meters to the surface in the Pacific, while some of the "Meteor" specimens were taken in net hauls to depths of 900 meters and the "Valdivia" specimens to depths as great as 2,500 meters. However, since these net hauls were not closing-net tows, little but speculative results can be gleaned from them and no exact information is available concerning the lower limits of the vertical distribution of *Tetraplatia*. The 44 specimens from Monterey Bay add a little information along this line since it appears from the 11 tows which captured *Tetraplatia* that in general the deeper the tow the more specimens were captured. These tows were continuous from the depth recorded to the surface and the number of specimens captured and depths reached were as follows:

Depth	*Number of Specimens*
510	1
620	2
775	1
846	3
870	2
890	2
960	4 (½ of sample only)
995	2
1,005	7
1,022	19
1,065	1

Tetraplatia, like most medusans, seems to be a rather omnivorous carnivore. Dantan (1925) seems to be the only other worker who has noted any of the food items of these animals and he found only a few specimens containing any identifiable food substances. He found the remains of an annelid larva, parts of a crustacean and a small chaetognath. In the specimens from the Pacific, also, only a few individuals have been noted containing identifiable food items. These included an immature euphausiid, a chaetognath and three copepods. Two specimens of *Tetraplatia* were noted whose mouths were widely flared, as if they had been attached to some rather large animal at the time of capture. An organism such as *Tetraplatia* can readily ingest another animal of its own bulk which was nearly the situation with the specimen found ingesting the chaetognath. This individual with the partly swallowed arrow worm is sketched in Figure 7.

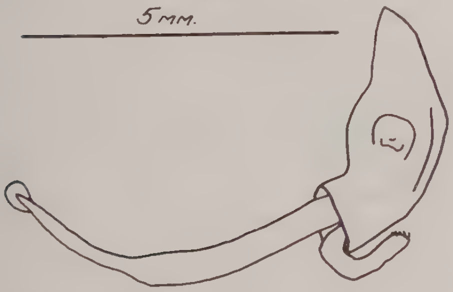

FIG. 7. A sketch of *Tetraplatia volitans* which had captured a chaetognath.

Nematocysts

Recently considerable attention has been turned toward the nematocysts of coelenterates. Weill (1934) used these structures to show phylogenetic relationships and Papenfuss (1936) and Hand (1954) have shown that these characters may be useful in the identification and separation of species. Russell (1938, p. 162) concurs with Weill that the study of nematocysts "may be of value in showing phylogenetic relationships," but questions their value as specific characters. In his elaborate study of 1934, Weill considered the nematocysts and affinities of *Tetraplatia volitans* and concluded that these animals were narcomedusans. He did not personally observe the nematocysts of this species but instead based his conclusions on the descriptions and figures of Viguier (1890).

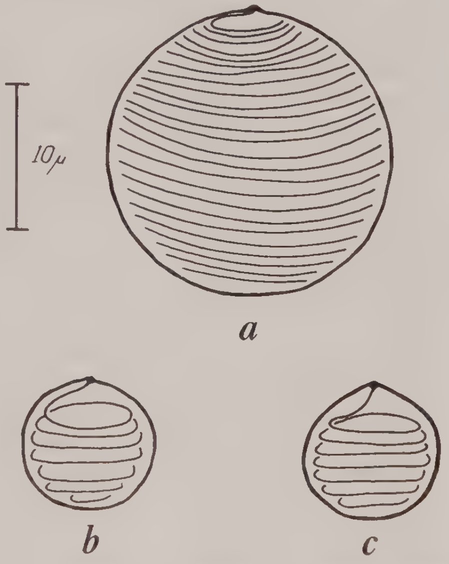

FIG. 8. Nematocysts of *Tetraplatia volitans: a*, a large atrich; *b* and *c*, small atrichs.

Contrary to Viguier's opinion Weill felt that the variability in the size of the nematocyst capsules was insufficient to recognize more than one category—atrichs. In the present state of our knowledge the Narcomedusae, the group to which *Tetraplatia* was assigned by Weill, may be stated to have a monocnidom of atrichous isorhizas (atrichs).

I have examined twelve specimens of *Tetraplatia volitans* to determine the cnidom of this species as it exists in the eastern Pacific. Nematocysts are rare or absent from most of the body and are largely confined to the nematocyst tracts, although near the distal end of the manubrium the tracts become diffuse and nematocysts are generally distributed over this area. Only one type of nematocyst has been found in the tissues of *Tetraplatia*, this being an atrichous isorhiza, although two very obvious size categories are present. The smaller capsules appear to contain a coarser thread than the larger, and the thread in the larger capsule has many more coils than the smaller. Figure 8 illustrates the appearance of these atrichs. The capsules are all very nearly spherical, with some tendency to develop a low conical shape toward the opercular region, at least in the smaller ones. The large atrichs are restricted to the manubrium in their occurrence while the smaller occur throughout the nematocyst tracts. Dantan (1925) indicated that he too found a large and small type of nematocyst, although he gave very little indication of their structure. The sizes of the two categories of atrichs were as follows:

Small—8–12 μ diameter
Large—18–22 μ diameter

Komai (1939) also found two sizes of nematocyst, one 20 μ in diameter, the other 8 μ. He did not indicate what type nematocyst these were but his sizes agree well with what I have found.

Statocysts

Both Viguier (1890) and Dantan (1925), in their illustrations of whole *Tetraplatia*, have indicated the positions which the statocysts occupy. Carlgren (1909) has also described their location although he did not indicate their positions by figures. These writers seem to agree that the statocysts are located on the oral sides of the lappets, one in the middle of each of the two major lobes of the lappets at the junction of the velum and the lappet proper. Dantan had some difficulty in locating the statocysts, due to the more or less contracted and coiled-up condition of the flaps, and had to rely on sections to locate them. A number of the *Tetraplatia* from the Pacific have been examined in which the lappets were fully extended and in excellent states of preservation. As was remarked earlier, the term "bilobed" as applied to the lappets, is something of a misnomer since the lappets actually are divisible into at least eight terminal lobes. Moreover, the statocysts are not located at the midpoints of the two halves of the lappets, but are to be found just to the outer side of the second bifurcation of the supporting core of the lappets, as illustrated in Figure 3. The statocysts occur in a raised knob of tissue, and in sections it appears that the lithocytes have been derived from the endoderm. Figure 2 illustrates a section of a lappet through a statocyst.

In considering the structure of the lappets one feature appeared which was of considerable interest. This is the morphology of the nuclei of the velar and endodermal cells. The nuclei of the velum show a remarkable flattened and multilobed polymorphic structure, which is reminiscent of the nuclei of polymorphonuclear leucocytes. This is also true of some of the endodermal nuclei of the lappets which show a gradual transition from ovoid nuclei near the lappet base to the flattened, polymorphic type in the distal lappet endoderm. Dantan (1925) also noted these curious nuclei and Komai (1939) concluded that all of the cells possessing these polymorphic nuclei were endodermal.

The fully extended lappets of three specimens were constructed as is shown in Figure

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3; that is, with the third bifurcation of the core of the lappet being wider on the outer than the inner side and with this lobe divided into two equal parts at its very tip. These lappets thus have ten terminal velar lobes. The fully extended lappets of three othe- specimens possessed unequal third bifurcar tions, but did not show the terminal division of the outermost lobe. The sizes of the specimens (3.2, 4.8, 5.0 mm.) which possessed ten velar projections were not significantly different from those which possessed only eight (2.4, 5.0, 5.2 mm.), and although one could easily assume that this variation in numbers of velar lobes is an age-correlated phenomenon it is not demonstrable as such from the data at hand. Attempts to determine the number of terminal velar lobes present on very small specimens (1 to 2 mm.) met with very desultory results. Most of these little animals possessed very tightly rolled lappets, and unrolling them is nearly impossible. On two specimens, however, it was possible to count eight terminal lobes on at least one lappet of each. The appearance of the division of the lateral terminal lobes, changing the number from eight to ten, may well be one which occurs fairly late in the development of these animals or may be a character which expresses itself in varying degrees.

DISCUSSION

Since Komai (1939) has so strongly espoused the contention that *Tetraplatia* is a scyphozoan, considerable thought has been applied to test the basis for his conclusions. Komai has used the "octamerous arrangement of organs" and the "entodermal origin of the gonad" as features of a scyphozoan nature and has compared the lappets to the arms of stauromedusans. He makes a special point of identifying the structures usually considered as the velum with the tentacles of the Stauromedusae and he points out that *Tetraplatia* also resembles the cubomedusans in its quadratic structure. Komai (1939, p. 248) finally concluded that ". . . *Tetraplatia* is a primitive scyphozoon, retaining many characters of the actinula stage" and that ". . . the fins are probably a homologue of the marginal lappets of the ephyra, though more highly differentiated." Komai lists five lines of evidence which have been used by others to point to the hydrozoan nature of *Tetraplatia*. These lines are as follows: 1. the resemblance of the sense-organ to that of the trachymedusae; 2. the ectodermal gonads; 3. the presence of a velum; 4. the absence of septa and gastral filaments; 5. the absence of cells in the mesoglea. Komai agrees that the sense-organ is hydrozoan in nature and says (p. 245) that ". . . this may be the most questionable point of the scyphozoon theory." He states that items 2 and 3 above are "based on erroneous observations" and that 4 and 5 "are largely larval features." I cannot agree with Komai's conclusions and I feel that he himself has made some erroneous observations and interpretations.

The sense organ (statocyst) of *Tetraplatia* clearly is hydrozoan in nature; this Komai readily admits although he refers to the lithostyle as a rhopalium. The origin of the gonads, although not observed as a developmental phenomenon, seems from a study of histological preparations to be clearly ectodermal. It is true that the gonads have invaded the coelenteron to the extent that they occur embedded in ridges of endodermal tissue but they can be seen to be covered with mesogleal tissue which separates them from the endoderm. Komai illustrates the position of the gonads where they approach the surface at the margin and shows the gonadial tissue covered by a thin layer of ectoderm. There is no indication of any mesoglea between the gonad and ectoderm but he says that mesoglea is inserted between the ectoderm and gonads. Among the six specimens, prepared as serial sections which I studied, five were ripe or nearly ripe adults (four females, one male) and one was an unripe immature individual of undeterminable sex. In the ripe specimens there is a very definite indentation or "pore" at the point where the gonads contact the surface (behind the buttresses and immediately below the marginal band), and in the male groups of sperm cells were in these pores, and in one female a large ripe egg was half in and half out of one of the pores. In the immature specimen there is a gradual change in cell type from the ectodermal cells to the gonadial cells at the points where the gonads reach the margin. There is no mesoglea separating the ectoderm from the gonad at this point nor is there a definite epithelial layer covering the gonad as indicated by Komai. The conclusion from this is inescapable and obvious that the gonad is ectodermal and is derived as an ingrowth of epithelial ectodermal tissue into the endoderm, carrying with it the mesoglea which encases the adult gonad.

The matter of the presence of a velum is a very difficult point. The hydrozoan velum is a solid structure consisting of two layers of ectoderm separated by mesoglea. The mesoglea may, however, be nearly nonexistent judging from illustrations of velar anatomy of many hydrozoans and indeed the demonstration of mesogleal tissue in an animal like *Hydra* is not simple. Komai has interpreted what Carlgren and Dantan have called *velum* as tentacles and described and drawn them as being composed of a core of polymorphonuclear endodermal cells covered by epithelial cells. I find two details wrong with this conclusion. First the polymorphonuclear cells are not endodermal, but are ectodermal and second these are not tentacles but are part of the velar sheet, two cells thick, the cells of the oral side being thin, flat epithelial cells while the aboral surface is the layer of polymorphonuclear cells. I cannot determine if there is any mesoglea present between these cell layers. In the slides I have examined some sections, through tightly rolled lappets, were rather similar to Komai's figure 9 (Komai 1939, p. 240), but this appearance is the result of the rolling and folding of the velum. In expanded lappets there clearly are no adoral appendages which could be interpreted as Komai has or which occur in the position Komai has indicated. Indeed, I find Komai's whole interpretation of the structure of the lappets to be incorrect. He has indicated that the lappets have on their oral surface a thin epithelial layer, next below this a layer of endodermal motor (muscular) cells with fibrous bases, below these another layer of endoderm (these contain the polymorphic nuclei), next the thick mesogleal layer which supports the lappets and then finally the outer-most layer of thin epithelium on the aboral surface. I find all these structures but cannot subscribe to his interpretations. There is a thin epithelial layer overlying a muscular layer on the oral surface of the lappets; however, both these tissues are ectodermal and are separated from the next layer, the endoderm, not by the fibrous bases of the motor cells but by a thin fibrous layer of mesoglea. A double sub-umbrellar layer of ectoderm is not an unknown feature in the Hydrozoa, the innermost layer being the muscular one. That the layer possessing polymorphonuclear cells is endodermal I do not question, since this layer can be traced through the serial sections and its confluence with the endoderm of the coelenteron is clear. Also the polymorphic nuclei gradually become regular ovoid nuclei near the base of the lappet and become identical in structure to those of the endoderm proper. The thickened aboral layer of mesoglea is a clear-cut structure as is the outer, aboral ephithelium and on their nature Komai and I agree. In my slides it is clear, however, that it is this latter, ectodermal, layer which gives rise to the cells with polymorphic nuclei of the velum and there appears to be no possibility that this could be an endodermal tissue in spite of the similarity of its nuclei and those of part of the endoderm.

Komai dismissed the absence of septa, gastric filaments and cells in the mesoglea as larval features. In the Scyphozoa the septa are well developed in the scyphistoma larva while the cellular mesoglea and gastric fila-

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ments make their appearance in the ephyra. Since Komai suggests the "fins" or lappets are the same as those of the ephyra, it seems curious that he could so readily dismiss the absence of these other structures in this animal, *Tetraplatia*, even though he concludes it is neotenic.

I find that I am in complete disagreement with Komai and can only conclude that he has not properly interpreted the structure of this hydrozoan. One further point might be mentioned, however, before the hydrozoan nature of this animal is assured and this concerns the nematocysts. Scyphozoans quite generally possess atrichs, although they, as well, also possess at least one other type, even in the earliest developmental stages (Weill, 1934). This would seem to be further proof that *Tetraplatia* is a hydrozoan, since its cnidom is identical to that of the Narcomedusae. There are certain gross characters of *Tetraplatia* which do suggest the Cubomedusae, and some such organism as *Tetraplatia* conceivably could have been involved in the early evolution of the scyphozoan line, although *Tetraplatia* is clearly a hydrozoan. The problem which now must be solved is, "Where among the Hydrozoa should *Tetraplatia* be placed?" I believe *Tetraplatia* is a trachyline medusa and will now discuss this.

The trachyline medusae are commonly considered to be composed of two orders, the Trachymedusae and the Narcomedusae. The Trachymedusae are defined as possessing free or enclosed lithostyles containing endodermal lithocytes, a simple bell margin and a monocnidom of microbasic euryteles. The Narcomedusae on the other hand possess only free lithostyles, a scalloped bell margin and a monocnidom of atrichous isorhizas. The Narcomedusae also lack a true manubrium and may have peronia and otoporpae. The life histories of the trachylines as a whole lack a polypoid generation and are said to be direct, involving a planula, an actinula, and the adult. The gonads of the trachylines are sub-umbrellar and occupy a position either below the radial canals or in the floor of the stomach pouches (Narcomedusae).

Tetraplatia has a number of characteristics which suggest its affinities to the trachyline medusae and especially to the Narcomedusae. Its swimming plates or lappets can be homologized with the lappets of Narcomedusae as can the adoral stomach pouches which run into the buttresses. Its nematocysts are also narcomedusan. Its sensory structures, the statocysts (enclosed lithostyles), however, are trachymedusan. The position of the statocysts on the adoral lappet surface is, however, an unusual position since all of the trachylines have marginal, ex-umbrellar balance organs. The position of the gonads, below the stomach pouches, is a narcomedusan character unless these pouches are actually homologues of the radial canals. Its manubrium suggests trachymedusan rather than narcomedusan affinities.

As an adult animal, *Tetraplatia* is grossly a very differently constructed medusa than any known Narcomedusae, in spite of its obvious narcomedusan nature. The lack of tentacles, radial and ring canals, and the position and structure of the sensory clubs make it unique. The flying buttresses and the swimming lappets also are without counterparts. The extreme reduction of the sub-umbrellar space gives this animal its non-medusan, planuloid shape.

Carlgren (1909) was so impressed by the peculiarities and unusual structure of tetraplatians that he erected a new order of medusae for them, the Pteromedusae, as a group of equivalent rank to the Trachymedusae and Narcomedusae. This action has not been accepted by other workers as a solution to the systematic position of these animals, and, as has been remarked previously, *Tetraplatia* is usually considered to be a narcomedusan. The Narcomedusae contain several unusual forms such as *Polypodium* and *Hydroctena* and some have very unusual, complicated life histories. In general a hydroid phase is absent in their life histories, although all known seem to involve an actinular larval stage. These actinulae are in general planuloid, tentacled organisms; the tentacles arising at the place on the circumference which demarks the aboral, ex-umbrellar, area from the oral, manubrial area. In the actinula in its simplest form there is no sub-umbrellar region, but as it grows into a medusa the bell margin grows outward and downward, thus creating the sub-umbrellar space. *Tetraplatia* in form and adult structure strongly suggests its actinular affinities and except for the absence of tentacles seems to be a compromise between the structure of actinula larvae and adult trachyline medusae.

There is very little information to guide us to a decision as to what position *Tetraplatia* should have among the Narcomedusae. Mayer (1910) reviewed the several possible classifications within this group, and recognized only two families, the Solmaridae and Aeginidae; the Solmaridae are without stomach pouches while the Aeginidae possess them. Unfortunately Mayer did not consider *Tetraplatia* at any point in his work. Of these two families of Narcomedusae, *Tetraplatia*, by its possession of a pouched stomach, seems to most closely approach the Aeginidae and within this family it would best be placed within the sub-family Cunanthinae.

Within the Cunanthinae can be placed such genera as *Cunantha*, *Hydroctena*, *Cunoctantha*, and *Cunina*. Of these genera *Tetraplatia* would seem to be most closely related to *Cunantha*, although Mayer (1910, Vol. 2, p. 449) said, ". . . the 'genus' *Cunantha* is, I believe, only a developmental stage of Aegina." *Cunantha* is, however, clearly a medusan and does not grossly suggest *Tetraplatia* by its form, but its special features do suggest some of the special features of *Tetraplatia*. For example, the ex-umbrella bears rows of nematocysts as in *Tetraplatia* and moreover *Cunantha* has only four broad lappets. The stomach pouches of *Cunantha* are very small and only four in number, again as in *Tetraplatia*. The tentacles of *Cunantha* are rudimentary whereas there are none in *Tetraplatia*. If *Cunantha* exists as a valid genus might not this last character indicate a trend toward loss of tentacles? However, the medusoid form, sensory clubs, numerous statoliths, otoporpae, and gonad ring of *Cunantha* all represent characters quite different from those of *Tetraplatia*.

Broch (1929) in reviewing the classification of the Narcomedusae recognizes three families, the Cuninidae, Aeginidae and Solmaridae. Of the three, again, *Tetraplatia* best fits the definition of the aeginids but at the same time cannot be clearly identified as an aeginid or indeed even as a narcomedusan if one considers its structure and particularly its possession of a statocyst.

Dantan (1925) did not believe that the statocyst of *Tetraplatia* could be considered as derived from the endoderm. Indeed, the whole statocyst is not, nor is it in other trachylines, although the internal cells of the lithostyle are. In *Tetraplatia* it seems to be fairly obvious that the lithostyles, or at least the lithocytes, are endodermal. This character then clearly places *Tetraplatia* among the trachylines. Dantan (1925, p. 452) although disagreeing entirely with Carlgren's classification of *Tetraplatia*, tried to conserve Carlgren's name, Pteromedusae, by making it a family of the Anthomedusae. This was a kind gesture on Dantan's part; however, it is an action contrary to the International Rules of Zoological Nomenclature under which the only allowable family name would have to be Tetraplatiidae if *Tetraplatia* is the type genus.

If *Tetraplatia* is to be placed among the Narcomedusae it will stand out as a very aberrant, highly divergent, form. Its possession of an enclosed lithostyle is a trachymedusan character and the definition of the Narcomedusae would therefore have to be modified to meet this situation. That *Tetraplatia* has strong narcomedusan characters certainly is not to be denied; however, it is an animal that seems to have evolved along a path quite distinct from the normal narcomedusan line. One can hypothesize that *Tetraplatia* is the result of retrogressive evolution from the aeginid line, or that *Tetraplatia* has evolved directly from primitive narcomedusan ancestors at a point so early that the true medusoid form had not yet been established. If this latter is true, then *Tetraplatia* must represent an early evolutionary experiment in developing a more complex organism than the presumed actinular ancestors of the trachyline medusae. Another suggestion could be that *Tetraplatia* represents a neotenic actinula, and as such might better be called aberrant than primitive. Regardless of which of these hypotheses one might subscribe to, I feel that the unusual characteristics of *Tetraplatia* place it in a position between the two recognized orders of trachyline medusae and that it is morphologically so distinct that it deserves to be placed in an order of its own. I therefore subscribe to the classification proposed by Carlgren (1909) and recognize *Tetraplatia* as a pteromedusan. Further light may be shed on the actual ancestry of *Tetraplatia* once its development and complete life history are known.

The distribution of *Tetraplatia* in the Eastern Pacific, as indicated in Figure 4, presents a pattern in the northern latitudes which one might predict on the basis of known ocean currents. That is, this animal seems to live in the water which slowly moves in a clockwise direction and makes up the North Pacific Current. On this basis one can predict that *Tetraplatia* can be expected to be found throughout this whole current system including the Kuroshio and the North Equatorial Current. Komai (1939) has already reported four specimens from Japan. Further collecting alone will test this suggestion. However, if one examines Figure 4, it will be seen that there is a considerable gap between the most southerly point at which *Tetraplatia* was collected and the main area from which most specimens were taken. That is, no specimens were collected between 5° south latitude and 20° north latitude. The area covered by the lack of specimens was sampled by the Scripps Institution cruise "Shellback" and the specimens taken at 20° N. and 5° S. were from that expedition. Although not all of the plankton tows taken on "Shellback" have been examined by the writer, 18 samples spaced throughout the gap have been examined and no *Tetraplatia* were found. The tows in this area were oblique hauls with a one-meter net fishing from 300 meters depth to the surface. The presence of one specimen of *Tetraplatia* at 5° S. suggests that *Tetraplatia* is present in the cooler waters of the South Pacific, since this specimen was from the northern end of the Peru Current, a cold water mass moving in a counter-clockwise direction. The gap between this cold water mass and the cold water of the North Pacific is filled with the warmer waters of the Equatorial Counter Current and *Tetraplatia* may be unable to live in this area of warmer water. This, perhaps, explains the absence of *Tetraplatia* in the area under consideration, although a possible alternative solution might be in the fact that colder waters underlie the area and *Tetraplatia* may be found there if samples are taken from the deeper waters. If this is so, then the lack of *Tetraplatia* may be an artifact of sampling and the result of tropical submergence as this animal stays in the colder waters which may offer to it a more suitable environment.

CONCLUSION

Tetraplatia volitans is considered, by the author, to be a highly specialized and divergent trachyline medusan of narcomedusan ancestry which has evolved a trachymedusan sense organ. Its adult morphology seems to represent a compromise between the structures of actinula larvae and adult narcomedusans. Its highly specialized lappets and new features such as the flying buttresses and enclosed adoral lithostyles represent unique characters. In order to give proper weight to the unusual nature of this animal, Carlgren's order of Pteromedusae is recognized as a valid classification. *Tetraplatia* is nearly worldwide in distribution and may be characterized as a holoplanktonic organism which undergoes diurnal vertical migrations.

ACKNOWLEDGMENTS

During the course of my work on *Tetraplatia* I have been materially aided by a number of people who have either collected specimens for me or called my attention to their presence in individual plankton samples. These people are Messrs. Berner, Bieri, Brinton and McGowan of the Scripps Institution of Oceanography, and Mr. Barham of the Hopkins Marine Station. I also wish to thank Dr. M. W. Johnson of Scripps, and Mr. G. F. Gwilliam of the University of California at Berkeley for a critical reading of the manuscript.

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CALIFORNIA FISH and GAME
"CONSERVATION OF WILDLIFE THROUGH EDUCATION"
VOLUME 41 APRIL, 1955 NUMBER 2

EARLY DEVELOPMENTAL STAGES OF THE CALIFORNIA BARRACUDA, *SPHYRAENA ARGENTEA* GIRARD[1]

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The California barracuda, *Sphyraena argentea* Girard, is a major commercial and sport fish along the coasts of Southern California and Baja California, but there are still many gaps in our knowledge of its early life history. Barnhart (1927) figured and briefly described the egg and newly-hatched larva, and Walford (1932) treated the spawning season and certain aspects of growth and maturity. Little additional information on this species has been published. Recent studies at Scripps Institution have shown the need for a more complete description of the egg and larval stages, to permit accurate recognition of barracuda material in plankton samples. As discussed below, it is thought that Barnhart's specimens were correctly identified but that his method of preservation obscured some important diagnostic characters. In the present paper the early developmental stages are described from studies on both living and formalin-preserved samples. Identification was established by the diagnostic somite count and by rearing larvae for several days after hatching, at which time they were unmistakably conspecific with small specimens in a graded series of postlarvae and juveniles in the collection of Scripps Institution.

EGGS

The pelagic eggs of *Sphyraena argentea* were described by Barnhart (1927) as "transparent; diameter 1.02 mm.; one oil globule, brownish, .20 mm. in diameter; zona radiata finely striated, covered with fine dots; yolk homogeneous. Perivitelline space small if any; embryo almost completely in contact with inner surface of envelope." Walford (1932) recorded the mature ovarian eggs as 1.14 to 1.6 mm. in diameter.

Eggs of the barracuda that I have studied, from fresh plankton samples off La Jolla, measure about 1.5 mm. in diameter. In early embryonic stages the egg is commonly slightly lopsided rather than fully spherical. In life, the capsule lacks any obvious texture, but some preserved eggs show a very minutely striated surface. The yolk of live eggs is colorless and very distinctly alveolar ("segmented"), the oil globule colorless or very pale buff. Preservation makes the yolk somewhat opaque, and its alveolar nature is then difficult or impossible to observe. The yolk texture is, therefore, a useful supplementary character for the recognition of live eggs of the barracuda, but it is of little value for the identification of this species in preserved samples.

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[1] Submitted for publication September, 1954. Contributions from the Scripps Institution of Oceanography, New Series, No. 770.

EMBRYONIC DEVELOPMENT

Barnhart did not mention pigment in the embryonic stages of the barracuda, and credited the newly-hatched larva with only two yellowish chromatophores. In reality, the advanced embryonic stages are heavily marked with both black and yellow cells, which have a well-defined migratory history and form distinctive patterns that greatly assist identification. The yellow cells fade after preservation but, for the sake of taxonomic completeness, this pigment is described in the stages for which live material has been available. The black pattern persists in specimens that are properly preserved.

The youngest pigmented embryo that I have seen thus far (Figure 1, A) had the embryonic axis well developed, and had a short tail bud. At this stage small black cells are abundant on the dorsal and dorsolateral surfaces. Anteriorly, the pigmented area divides into two dorsolateral bands that rejoin transversely across the posterior part of the midbrain, leaving the area above the hindbrain free of pigment. There are a few black cells over the ventro-lateral surfaces of the tail somites, and a few extend down the posterior surface of the yolk sac toward the level of the oil globule.

In a slightly more advanced embryonic stage, examined alive, the tail bud is longer and its median fin folds are somewhat better defined, though they are still simple ridges. Melanophores more extensively invade the sides of the somites and extend back along both dorsal and

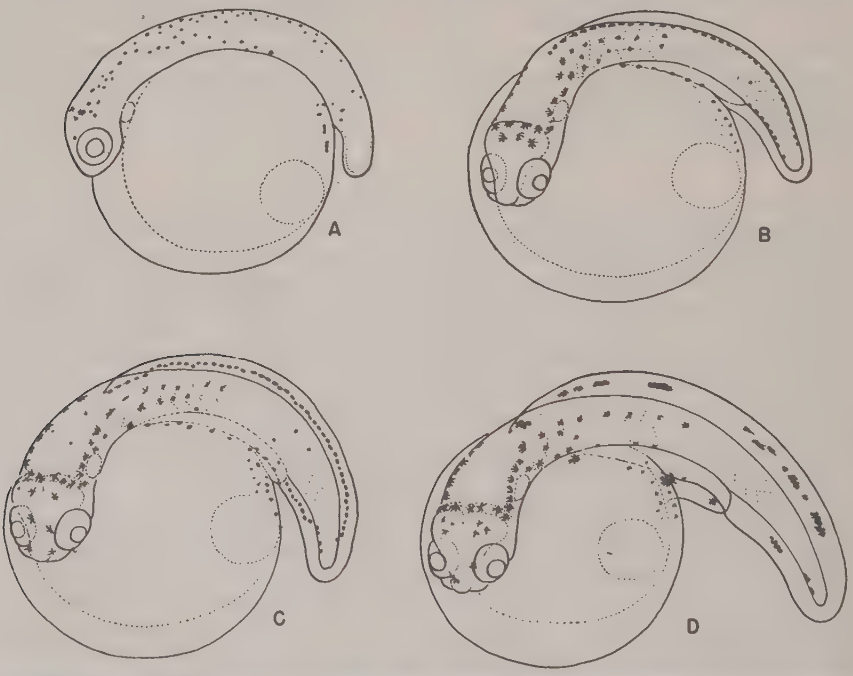

FIGURE 1. A, B, C, D—Embryonic stages (egg capsules omitted). This figure is based on preserved eggs, and thus the yellow pigment and yolk texture are not shown. B, C, and D are drawn in the same standardized position, to simplify comparisons.

ventral surfaces of the tail bud. The dorsal pattern on the "neck" (the area between the midbrain and the pectoral region) has simplified into a diagrammatic shield-like design (as in Figure 1, B, C, D). The black cells on the posterior surface of the yolk sac are in an irregular, more or less double, row. There are no melanophores on the oil globule. In addition to the black pigment this stage has, in life, a conspicuous yellow pattern, which is pale yellow in reflected light and brownish orange-yellow in transmitted light. The yellow cells are distributed in blotches and irregular patches, chiefly as follows: one or more behind each eye; several scattered irregularly along the dorsal and dorso-lateral surfaces of the body; an irregular band along the ventro-lateral surfaces of the somites, approximately in the pectoral region; a pair of dorso-lateral and a pair of ventro-lateral blotches just posterior to the base of the tail bud; and a patch on the postero-ventral surface of the yolk sac, over the region of the oil globule.

In successively more advanced embryos (Figure 1, B, C, D) the tail lengthens and its median fin folds expand, and the gut lengthens until it extends a moderate distance beyond the posterior surface of the yolk sac. Concurrently, the melanophore pattern undergoes a conspicuous sequence of changes. The pattern on the "neck" remains simple and diagrammatic. Posterior to it melanophores assemble in a sharply defined mid-dorsal line along the base of the developing dorsal fin fold, and a similar mid-ventral line of melanophores assembles along the base of the ventral fin fold (Figure 1, B). As the fin folds enlarge, the median lines of black cells move out into the respective dorsal and ventral folds. Here they at first retain their linear alignment (Figure 1, C), but then aggregate into a series of disconnected blotches (Figure 1, D). On the basis of present knowledge, it is not clear whether the movement of melanophores into the fin folds results from active migration or whether the cells might be transported passively along with the outward growth of connective tissue that forms the fin folds. The preliminary movement of the melanophores onto the mid-dorsal and mid-ventral lines (particularly the latter) probably results from active migration.

Before hatching, the prolarval pigmentation (described in detail below) is essentially complete. Particularly distinctive are the dark blotches in the fin folds, the pattern on the neck, and the failure of the oil globule to acquire a cap of melanophores. A similar pattern on the neck is recognizable in embryos of various other fishes, but in the barracuda it is unusually diagrammatic and is retained into more advanced developmental stages than in any other form that I have studied thus far. Likewise, development of black pigment in the median fin folds is not unique to the barracuda, but in the particular details of this pattern sequence the barracuda differs from other California fishes that have been described thus far.

The eggs and larvae on which Barnhart based his brief description were probably correctly identified. His outline drawing of the newly hatched larva, apparently guided by a camera lucida, is essentially correct in morphological features, including the unusual combination of somites (14+11) that characterizes the barracuda. The most conspicuous discrepancy is in pigmentation, and this can probably be attributed to the effects of preservation. Barnhart's specimens have not been located, so it is not known whether they were preserved in Bouin's solution or in weak formalin. Bouin's is a common embryological preservative, and Barnhart is known to have used it in some cases, but its property of fading melanin makes it undesirable for use with materials that are intended for taxonomic study. Weak formalin, 5 percent or less, is a poor fixing solution for fish eggs and larvae; it not only fails to retain the black pigment adequately but does not preserve morphological characters properly, and produces soft, fragmented specimens. The use of 10 percent formalin is strongly advised. Standard plankton samples preserved in this way remain in excellent condition for study. Embryos and larvae of the barracuda preserved in 10 percent formalin in 1951 and 1952 still retain their melanophore patterns; others that were preserved in weak solutions now show little or none of the diagnostic pigmentation and, in addition, their morphological characters are poorly preserved.

THE PROLARVAL STAGE

The prolarval stage is defined as that part of larval development between hatching and the complete disappearance of the yolk sac (Hubbs, 1943). In the California barracuda, this stage lasts about three or four days under laboratory conditions.

Barnhart (1927) reported the prolarva of the barracuda to have "* * * a large globular yolk-sac; total length, 2.25 mm.; length, snout to anus, 1.50 mm.; anus, one-third the distance from posterior edge of yolk-sac to end of caudal fin. Pigmentation very scarce; two yellowish chromatophores, one just above anus, and above it a larger one on the dorsal surface."

The characters of the newly hatched larva and the subsequent changes during the brief prolarval period are here redescribed from fresh material. The descriptions are based on living specimens except where otherwise stated. The yellow pigment cells and the alveolar structure of the yolk are conspicuous in life and contribute to a well-rounded knowledge of the taxonomic characters of this species, but both features are lost more or less completely in preserved specimens, and hence are of limited usefulness for the identification of preserved plankton.

The *recently hatched prolarva* (Figure 2, A) is about 2.5 mm. long. The large ovoid yolk sac is colorless and transparent, with distinct alveolar or "segmented" structure. The posteriorly placed oil globule is colorless or pale buff. The head is still embryonic; the eyes and ear capsules are conspicuous, but the jaws have not yet formed. The pectoral fin buds are very small. The moderately long gut extends well posterior to the end of the yolk sac. Median fin folds are well developed; the dorsal fold begins above or slightly behind the midbrain, and there is a moderately long preanal fold. The somites typically number 24 or 25 (14 on the body, 10 or 11 on the tail). Both black melanophores and yellow cells are abundant. The yellow cells are aggregated in blotches, chiefly as follows: one behind each eye; a pair on or near the prospective jaw position; two pairs along the ventro-lateral surfaces of the trunk somites, respectively anterior and

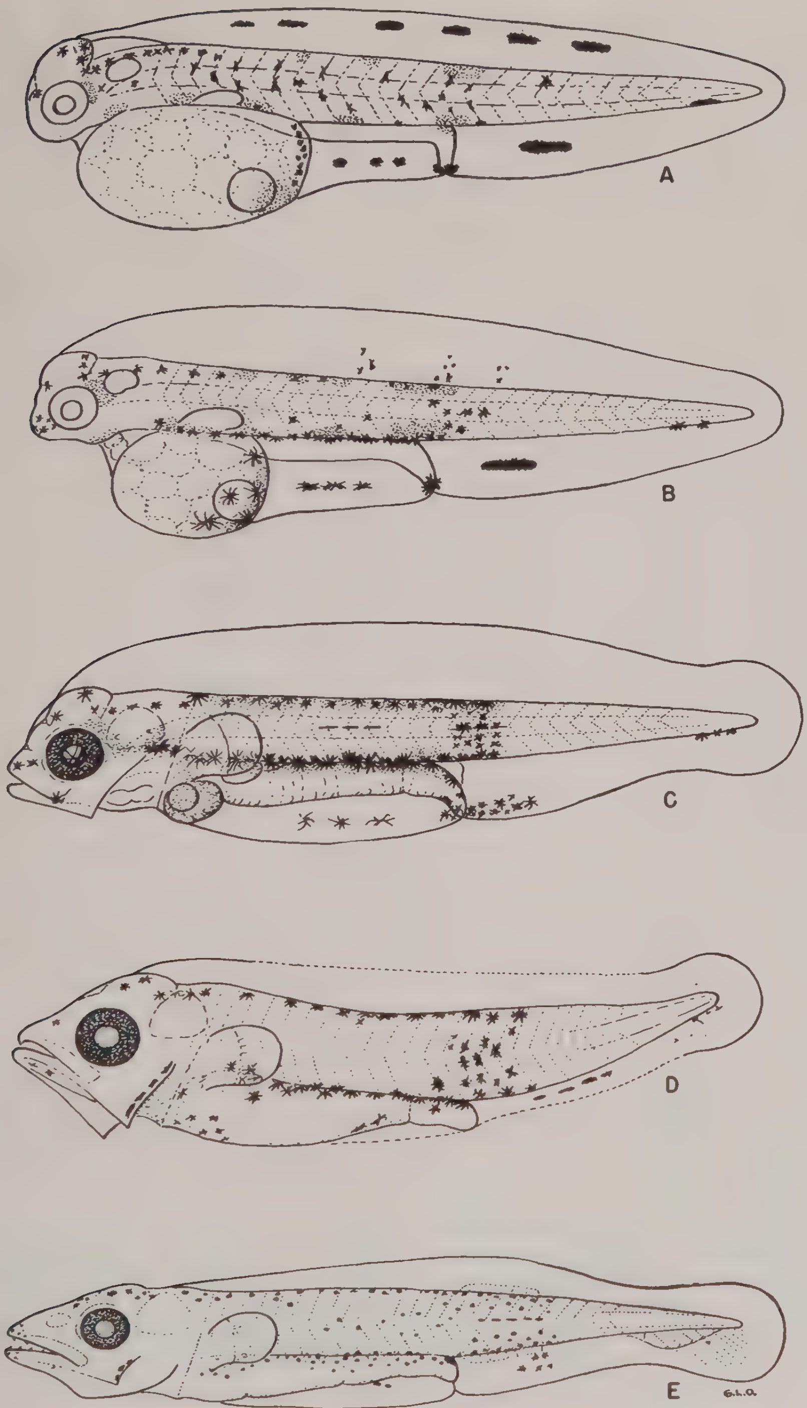

FIGURE 2. A—Recently hatched larva. Total length about 2.5 mm. A, B, and C are based on live specimens, and thus show the areas of yellow pigment (represented as stippled blotches) and the alveolar structure of the yolk. B—Larva one day after hatching. C—Larva three days after hatching. D—Larva about 4 mm. in total length. E—Larva about 7 mm. in total length.

posterior to the pectoral fin buds; a pair of large blotches above the angle of the hindgut, and above them a large mid-dorsal blotch on the top of the somites at the base of the tail; an additional yellow patch on the yolksac over the region where the oil globule adjoins its surface; a few small yellow spots are variously scattered along the back. The pattern of black cells provides a *combination* of characters conspicuously unlike that of known prolarvae of other local fishes. The neck bears a pair of dorso-lateral rows of black cells that join across the back of the midbrain, leaving the top of the hindbrain conspicuously free of pigment; along the sides of the body amoeboid black cells are conspicuously associated with the myocommata, along which they are apparently migrating. An irregular double row of black cells extends down the posterior surface of the yolk sac to the level of the oil globule. The median fin folds are conspicuously marked with black blotches; they vary somewhat in number and arrangement, but typically the preanal fin fold has from one to three, the ventral fin fold usually a single blotch, and the dorsal about six, some of which may be more or less confluent. There are scattered melanophores on the snout, along the gut, in the anal region, and in a ventral blotch near the tip of the tail. The oil globule lacks black pigment.

The *day-old larva* (Figure 2,B) shows conspicuous changes but is still in a very embryonic condition. The yolk sac is reduced and more rounded; it is now entirely posterior to the head and is only about half the length of the gut. The yolk is still conspicuously alveolar. The head is somewhat larger, the snout projects slightly, and the jaw rudiments form a distinct bulge on the lower surface. The pectoral fin buds have enlarged, but are still embryonic. The pigmentation is intensified. The yellow chromatophores are now brilliant yellow-orange in both reflected and transmitted light, and the aggregations of these cells have enlarged. The yellow blotches behind the eyes and those anterior and posterior to the pectoral fin buds are paired; those along the dorsal surface of the somites are median; those along the lower edges of the posterior body somites are now apparently confluent across the median line. The pattern of black cells on the neck persists. Most of the black cells that were migrating downward along the sides of the body have reached the lower edges of the somites, and there form a dense double row; dendritic black cells have spread outward irregularly over the posterior surface of the yolk sac. Conspicuous patches of melanophores persist in the ventral and preanal fin folds, but those in the dorsal fin fold have broken up and the individual cells are withdrawing downward toward the somites. A few black cells are scattered along the mid-dorsal surface of the body somites, and a new group is assembling on the sides of the somites at the base of the tail.

The *two-day larva* (not figured) has advanced greatly. The yolk sac is reduced to a globular mass smaller than the head. The pectoral fins are functional. The ear capsules are greatly enlarged, the jaws have formed, and the snout profile slopes moderately. The large eyes are heavily pigmented. There is a pair of large yellow blotches behind and internal to the eyes, a pair on the lower edges of the somites in the pectoral region, about three large and more or less confluent me-

(334)

dian blotches along the top of the gut, and about three long, vaguely defined yellow bars along the top of the body somites. The embryonic pattern of black cells on the neck persists, but is variably distinct, depending on whether the pigment in the cells is dispersed or concentrated. A double row of large, closely spaced melanophores extends along the top of the gut. A moderate number of smaller black cells is scattered along the dorsal and dorso-lateral surfaces of the body, and a diffuse band of black cells encircles the base of the tail. The dorsal fin fold is now free of black pigment, or has only one or two stray cells, but aggregations of black cells persist in the preanal and ventral fin folds. The pectoral fins are unpigmented. A few melanophores dot the surface of the snout, and there are a few internally in the snout, apparently underlying the forebrain.

The *three-day larva* (Figure 2, C) still has the greatly reduced oil globule and a small remnant of the yolk sac. The snout profile slopes moderately. The well-developed jaws are snapped occasionally, and the larva sometimes bends into an S-curve and then darts forward abruptly, as though pouncing on something. These activities are doubtless preliminary to feeding behavior, though I have not observed actual feeding at this stage. The air bladder is clearly visible; the gut is enlarged and has thickened, annulated walls. The somites typically number $14 + 10 = 24$, agreeing with the vertebral count of the adult (Clothier, 1950). The basic color pattern is little changed, but the colors and the pattern are somewhat intensified; this is especially true of the pigment centers along the dorsal surfaces of the body, the top of the gut, and the band around the base of the tail. In addition to black and yellow cells, the dorsal surfaces of the body and the base of the tail now bear iridescent coppery-greenish or bluish pigment (probably guanine). This combination of colors gives the living larva a distinctly greenish or bluish sheen macroscopically.

Larvae *four days old* are capable of feeding, and one was observed to feed heavily on nauplii of the brine shrimp, *Artemia salina*. It seems probable that, with reasonable care, barracuda larvae could be reared in the laboratory, at least through the earlier postlarval stages.

As in many other marine fishes that have small pelagic eggs, the chromatophores of the California barracuda develop pigment quite early, and part of the migratory history of these cells can be traced readily in the embryos and larvae. Of particular interest in this species is the complex sequence of cell movements involved in the formation and subsequent partial withdrawal of the pattern in the fin folds. A general discussion of pigment cell migration and early pattern formation in fishes has been given elsewhere (Orton, 1953). An understanding of how the extensive pattern changes of young fishes take place enables one to interpret differences and resemblances in these pigment characters more critically and to use them more effectively in identification, especially in piecing together conspecific series of developmental stages from the very heterogeneous material in plankton samples. On a small scale, this illustrates the value of basic research in paving the way for the improvement of applied techniques.

EARLY POSTLARVAL STAGES

The fish collection at Scripps Institution contains a number of postlarvae and juveniles of *Sphyraena argentea.* The smaller specimens are only slightly more advanced than three- and four-day-old larvae reared from eggs, and they grade into juveniles of unquestionable identity. Two small postlarvae are described here. Both are somewhat distorted as a result of preservation, and their length measurements are approximate.

Four mm. larva (Figure 2, D). This specimen now measures about 3.5 mm. in total length, but the somites are greatly contracted and the actual total length was probably about four mm. in life. There are about 14 somites on the body, about 10 on the tail. The head is moderately large, the strongly developed jaws are pointed and protrude somewhat, and the angle of the lower jaw is sharply pointed. The small pectoral fins are not yet rayed, and there are no pelvic fin buds. The median fin folds, which are still simple, are damaged and their extent is somewhat uncertain; the dorsal fold arises on the midbrain, and there are still traces of a preanal fold. The gut is moderately long, straight posteriorly. The melanophore pattern is still much like that of the three-day larva. Large melanophores are closely crowded along the dorsal surface of the body and the base of the tail. Anteriorly, the pattern forms two dorso-lateral lines of melanophores that continue forward lateral to the hindbrain and join transversely across the rear edge of the midbrain. This linear arrangement on the neck persists from the embryo with little change, an unusually long retention of an embryonic pattern element. Black cells are numerous along the top of the body cavity, and a conspicuous band of them encircles the base of the tail. There is a large median black cell on the forebrain, a few small ones on the snout and jaws, and a row margins the posterior angle of the jaw. The ventral fin fold bears a group of black cells at the mid-tail level, and a few enter the fin fold at the tip of the notochord. A few additional black cells are variously scattered over the belly and throat. The pectoral fins still lack pigment.

Seven mm. larva (Figure 2, E). This small, moderately slender, narrow-headed larva already resembles juvenile stages of the barracuda quite strongly, especially in the contours of its rather narrow, beak-like jaws. The angle of the lower jaw is very sharply pointed and its concave posterior margin is edged with confluent melanophores. The gut is moderately long, and is straight posteriorly. The pectoral fins are still simple, nonrayed, and the pelvics have not yet appeared. Basal elements of the anal (nine) and second dorsal (count uncertain) fins are forming, and hypural and caudal ray rudiments are present, but the tip of the notochord is still straight. The median fin folds are still moderately high; the dorsal fold begins above the hindbrain, and the preanal fold extends forward nearly to the pectoral region, as in earlier stages. The principal aggregations of black pigment cells that formed in early stages are still recognizable, but the originally sharp outlines of these pattern elements are now somewhat blurred by the increased abundance of pigment cells. The dorsal fin fold is unpigmented, the preanal fold has two small melanophores, and the ventral fold has about six. There are moderate numbers of small melanophores on the top of the head, along the dorsal surfaces of the body and anterior half of the tail, and along the upper sides of the belly. There are a few on the sides of the body somites. The basal half of the tail is more heavily pigmented with surface melanophores than in earlier stages, and in addition its mid-lateral septum bears a short row of linear cells. A few black cells occur around the tips of the jaws.

COMPARISONS

The developmental characters of Pacific Coast fishes are still too incompletely known to permit adequate listing and discussion of species with which the eggs and larvae of *Sphyraena argentea* might be confused. Hence, no extensive comparisons are attempted in this paper.

Advanced embryos and prolarvae of carangid fishes share with the barracuda the characters of alveolar yolk, moderately long gut, and somewhat similar body pigmentation, but carangids differ in having the oil globule in the anterior end of the yolk sac and capped with melanophores, fin folds without black patches (but commonly with *yellow* patches in life), no band of melanophores encircling the base of the tail, different somite count, and other differences in structure and pigmentation.

Walford (1932) noted that little has been published on the biology and life history of any of the barracudas of the world. Judging from experience with other groups of fishes, it may be expected that in general the early stages of the various barracudas will show a close group resemblance in basic morphological characters and probably in certain features of pigmentation. In a preliminary search of the literature I have found information on early stages of only one other species of barracuda, *Sphyraena sphyraena* Linnaeus in the Mediterranean (Vialli, 1937; Plate 35). This plate figures 11 stages, in color. It is accompanied by captions, but there is no descriptive text. The figured stages are chiefly juveniles, but there are four larvae, ranging from an advanced prolarva about 4 mm. long to a postlarva about 6 mm. long. These larvae fall between various stages of *S. argentea* that I have seen, but they correspond sufficiently to permit useful comparisons. There is a close agreement between the two species in general morphological characters and in some of the basic features of pigmentation, and there are differences in details that are probably of specific value. The two forms agree in early development of heavy pigmentation along the upper and lower surfaces of the body somites and the top of the body cavity, and in the presence of black pigment in the median fin folds in early stages and its reduction or loss in later stages. On the basis of this plate, *S. sphyraena* appears to differ from *S. argentea* in the extension of heavy dorsal and ventral pigmentation farther backward along the tail, nearly or entirely to the future base of the urostyle; the development of a mid-lateral line of melanophores along most of the length of the tail rather than a band of cells encircling the base of the tail; the presence of a mid-ventral line of black pigment from pericardium to anus; and the retention of the fin-fold pigment in series of small and rather evenly-spaced black dots (individual melanophores?) in contrast to its aggregation into blotches in *S. argentea*.

These differences suggest possible trends of larval variation to be expected in other barracudas. There is apparently nothing known concerning the early stages of the other eastern Pacific forms. Fowler (1944) listed only two; *S. ensis* Jordan and Gilbert (type locality, Mazatlan) and *S. idiastes* Heller and Snodgrass (type locality, Galapagos). However, Mr. John E. Fitch informs me that the dominant barracuda in the Gulf of California is an undescribed species, under study by Dr. George S. Myers, and that the range of this new form extends northward outside the Gulf at least to Cedros Island. Between San Juanico Bay and Cedros Island, at least, it overlaps the southern limits of the California barracuda. It would be useful to know how to separate these forms in early developmental stages. Toward this objective, sphyraenid eggs and larvae should be watched for in plankton samples taken along both the Pacific and Gulf sides of Baja California.

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printed in CALIFORNIA STATE PRINTING OFFICE

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WARM MARINE CARBONATE ENVIRONMENTS AND DOLOMITIZATION[1]

by

Rhodes W. Fairbridge[2]

ABSTRACT: Modern marine carbonate environments do not correspond precisely to the ancient ones, qualitatively or quantitatively. General classification of marine sediments should be redesigned to include Pelagic, Terrigenous, Volcanic and Biohermal (where "biohermal" is taken to mean all the sediments associated with organic reef structures, massive, clastic or chemical). Both pelagic and biohermal suites may be largely carbonate, and the others may contain smaller quantities. In origin the bulk of modern carbonates are organic or organogenic, being partly neritic, partly bathyal (pelagic). In view of the organic origin of petroleum, a basic genetic relationship exists with carbonate environments.

In the past the bulk of limestones were laid down in neritic environments. Their formation would be favored by thalassocratic sea-level conditions. In these warm shallow regions large amounts of magnesium carbonate were concentrated within organic calcite crystal lattices. This is the only important source of marine magnesium carbonate, but the resultant solid solutions are unstable. This leads to mobilization of small amounts of Ca and Mg ions which, in an alkaline medium (under reducing conditions and a high pH) and an unlimited supply of additional Mg ions (from sea or connate water), provides a potential source of dolomite. Under thermodynamic control, dolomitization may proceed at any appropriate stage of diagenesis, from soon after sedimentation to the post-orogenic period.

Introduction

The problem of carbonate sedimentation is examined, in this paper, as an aspect of normal marine geology; particular problems, associated with special environments such as evaporite lagoons, fresh-water lakes, the karst cycle, etc., will be excluded from the discussion. Within the marine realm, only the warm, shallow environments of the temperate and tropical oceans will be treated in detail. Under diagenesis only the neritic carbonates appear to favor dolomitization.

Place of Carbonates in Classification of Marine Sediments

There is a good deal of confusion about the place of carbonates in the various schemes of marine sediment classification. Unfortunately there are serious gaps. Following upon the fundamental work on modern deep-sea sediments carried out by the *Challenger* Expedition in 1873-76, Sir John Murray and A. F. Renard (1891) proposed that all marine sediments might be divided into either a pelagic or a terrigenous group. This has become the classical and very generally accepted method. According to Murray and Renard (1891, p. 186), the two groups may be subdivided as follows:

(a) Pelagic
  (i) Inorganic: red clay;
  (ii) Organic (or Biogenic): calcareous oozes (globigerina, pteropod, coccolith oozes);
    Siliceous oozes (radiolarian, diatom oozes);

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[1] Contribution from the Scripps Institution of Oceanography, University of California, New Series No. 771, La Jolla, California.

[2] University of Western Australia; as of 1st. July, 1955, Columbia University, New York, 27. This paper was delivered on an A.A.P.G. Distinguished Lecture Tour in Texas, Oklahoma and New Mexico in October, 1954.

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(b) Terrigenous

- (i) Blue, green and red muds;
- (ii) Volcanic mud;
- (iii) Coral sand and mud.

Strictly speaking, Murray and Renard employed this genetic classification only for deep-sea deposits, and not for neritic and shallow oceanic environments. Unfortunately some of their successors assumed that it was an all-embracing system for marine sediment classification. Geikie (1903) expanded it so that the terrigenous group would take in: A. Shore deposits, and B. Infra-littoral or Deeper Water Deposits.

Revelle (1944) found that oxidation and color changes in any case rendered the terrigenous group difficult to handle and suggested that like the pelagic, it should simply be divided into two main types: (i) Organic muds (i.e. reef derivatives, etc.) and (ii) Inorganic muds. Striving further toward completeness, Shepard (1948) added a Glacial class, and restricted the terms terrigenous and pelagic to allow Red Clay and the Volcanic Sediments to stand by themselves: (i) Red Clay, (ii) Pelagic Oozes, (iii) Terrigenous Muds, (iv) Glacial Marine Sediments, and (v) Volcanic Sediments.

A different approach was made by Kuenen (1950), who grouped marine sediments according to location (i.e. environment) in the primary division. Thus, he considered Shelf Sediments and Mixed Environments (littoral, delta, lagoon and estuarine) as well as the Deep-sea group, in which, beside the usual Pelagic class, he recognized a class of "Hemipelagic and Terrigenous" that included the terrigenous muds, volcanic, coral and carbonate muds. Considerable virtue is seen in the environmental approach, it being especially useful in consideration of facies. However, it might be improved by the recognition of special pigeon-holes for reef environments, marine volcanic associations and the marine glacial sediments.

Nevertheless, in none of the existing proposals, is there an adequate place for all the allied sediments that are associated environmentally, chemically or biologically with the organic reef-carbonate complex.

It is felt, in any case, that a descriptive and genetic classification is needed side by side with the environmental. Thus the writer, especially in his work on carbonate sediments, has found that yet another modification of the Murray and Renard plan may be more convenient. It has been used and tested informally in university lectures and laboratory work for some years now. Its special feature is that it may be applied to ALL marine sediments, deep-sea, neritic and mixed. It is not based on location, i.e. environment, but on readily observable features of composition. This is felt to be important since the recognition of major sub-oceanic currents, density flows, gravitational slumps and tectonic slides on the grand scale, all may ultimately result in the movement of shallow-water sediments into deep-water environments. Thus it is increasingly difficult to be sure just where a sediment was originally laid down, and so a classification that rests essentially on observable petrological and biogenic characteristics and not on assumed environmental conditions, is a surer if not more logical procedure.

The writer's proposal is as follows:—

(a) *PELAGIC*	(distinguished *not* necessarily by their location on the deep-sea floor but by fineness of grain (of the inorganic constituents), oxidation as evidence of slow deposition, and eupelagic biota); (i) Inorganic (stable end-products of terrigenous, volcanic and extra-telluric origin; chemical alteration products and precipitates); (ii) Organic (siliceous; calcareous; carbonaceous).
(b) *TERRIGENOUS*	(distinguished as products of mechanical land weathering, and transported by air or fluvial means, biological or ice rafting, wave or current; but *not* including volcanic explosion). Subdivided on basis of grain size and mineralogy.
(c) *VOLCANIC*	(an exclusive group, not directly related to subaerial weathering processes, and transport may be by gravitational flow, eolian action or by water). Subdivided in the same way as terrigenous deposits.
(d) *BIOHERMAL*	(an association of organic reef character, biohermal and biostromal deposits, including clastic and chemical derivatives, transported from the reef nucleus by wave, current and gravitational means). (i) Massive (ii) Clastic (iii) Chemical.

It may be noted that Sverdrup *et al.* (1942) worked out six classes of constituents for marine sediments, corresponding more or less to the principal components of the above groups: terrigenous material, products of vulcanism, remains of organisms, inorganic precipitates, chemical transformation products and extra-telluric material. However, it is clear that these are genetic *components,* and not classes of sediment. Thus chemical transformations occur mainly in the terrigenous and volcanic categories, and extra-telluric material is recognizable only in the pelagic types.

Ancient Carbonate Environments

In his analysis of ancient marine limestone environments, Sloss (1947) identified three distinctive facies:—

(a) *Platform*: characterized by thin, widespread, light-colored rocks, often richly fossiliferous and extensively dolomitized in many regions.

(b) *Basin* (i.e. parageosynclinal, in the sense of Stille, 1936): marked by similar sediments, but locally thickening, passing partly into reefs, also into barred basins.

(c) *Geosynclinal* (i.e. orthogeosynclinal): in thick sequences, alternating with deep-sea shales, black in color and siliceous.

In searching for the modern counterparts of these rocks the marine geologist is set a number of serious problems. Carbonates, by their unstable nature, become diagenetically altered with great rapidity. Metasomatism, e.g. to dolomite, may take place at any stage, often progressively and repeatedly. Fossils or other organic traces are frequently obscured or even expunged from the record during these processes.

Further, the geographic conditions of today do not necessarily match the paleogeographic conditions of the past, say, the Silurian, when a number of different and unfamiliar environmental factors may have been brought to bear. The paleoclimatology may have been different; the salinity and temperature of the sea water different; the CO_2 of the atmosphere probably varied with occurence of volcanic cycles; the sea-level and the distribution of the warm shallow platforms and basins were certainly varied from time to time; the duration of the average sedimentary cycle during the Paleozoic was far longer than the incomplete cycle of the present day, for our contemporary sea-level has only been within 10 feet of its present stand during the relatively short period of six or seven thousand years, owing to the comparatively recent cessation of the last glacial stage.

There appears, in any case, to be a fundamental difference between the world picture of carbonate sedimentation before and after the Cretaceous period, when pelagic foraminifera rose to a dominant position in the open-sea environment. This, as Kuenen (1950) has pointed out, has affected the whole calcium economy of the earth, because the present-day pelagic sedimentation is carrying carbonates to the bottom of the deep-sea; the great deep-sea basins ("thalasso-cratons") are now believed to be essentially as permanent and as structurally stable as the continental shields, so that once these deep-sea oozes have been laid down there is little chance of their ever being elevated and re-eroded. Thus a constant drain on the earth's $CaCO_3$ supply has been going on since Cretaceous times.

Prior to the Cretaceous the bulk of the earth's carbonates appear to have been in the neritic suite, but since then there has been a slight diminution of shallow water shelf areas and a great increase in the pelagic biota.

Any study of the Quaternary epoch leads to the conclusion that world-wide oscillations of sea-level of the order of two or three hundred feet is an automatic accompaniment to glaciation and deglaciation. Study of world paleogeography suggests that for each period of geological history there were stages of particularly high sea-levels, and particularly low ones. Such oscillations, termed "eustatic" by Suess (trans. 1904), are not necessarily glacially controlled; changes in the shape and volume of the major ocean basins and geosynclines would also lead to big changes in sea-level, in fact of greater magnitude than the glacial. Thus we have the terms "glacio-eustatic" and "tectono-eustatic". Continued sedimentation and filling of the basins also leads to rises in water-level, thus "sedimento-eustatic".

Regardless of origin, eustatic oscillations, by definition being world-wide (apart from the locally mobile areas), will lead to characteristic effects and formations, period for period, The broad effects may be readily perceived from an examination of world paleogeographic maps. Consider, for example, a world map of the Upper Cretaceous (Senonian stage): transgressions

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reached far and wide across every continent; this is what is known as a thalassocratic stage, the sea dominating the earth. In contrast, take the Lower Trias: long narrow geosynclinal troughs and numerous land-locked interior basins, one of the greatest regressive stages in history: an epeirocratic or continental time.

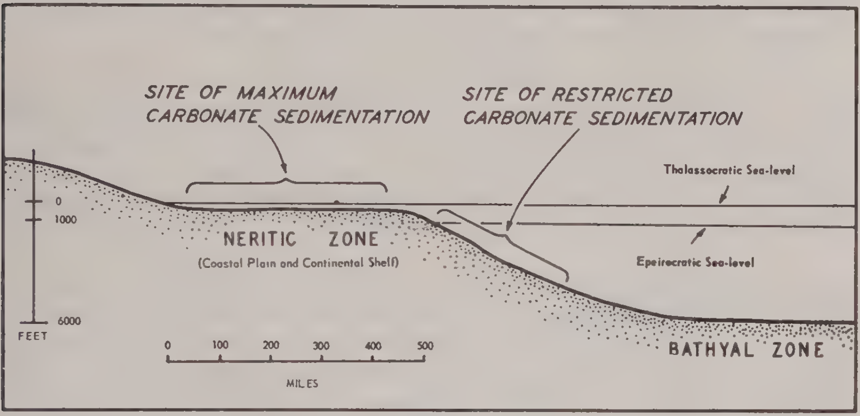
SITE OF MAXIMUM CARBONATE SEDIMENTATION
SITE OF RESTRICTED CARBONATE SEDIMENTATION
Thalassocratic Sea-level
Epeirocratic Sea-level
0
1000
6000
FEET
NERITIC ZONE
(Coastal Plain and Continental Shelf)
BATHYAL ZONE
0 100 200 300 400 500
MILES

FIGURE 1

Diagram illustrating a typical continental-oceanic border. Note that, prior to the introduction of pelagic foraminifera, maximum carbonate sedimentation in the neritic zone will coincide with periods of thalassocratic transgression. On the other hand, during epeirocratic stages, carbonate sedimentation will be reduced to a minimum because the sea-floor drops away sharply to bathyal depths which are unfavorable to carbonate sedimentation.

Such oscillations between thalassocracy and epeirocracy, like political swings, will leave an indelible effect on the earth, particularly in the low coastal areas, easily swamped, and on the continental shelves. Since we recognize that the bulk of the older limestones are neritic, warm water products, their formation will be greatly favoured by thalassocratic transgressions; thus the Upper Cretaceous contains chalky sediments almost all over the world. However, during the epeirocratic stages, the neritic seas will withdraw from the coastal plains and continental shelves to abut the steep continental slopes, which quickly drop away into bathyal depths, beyond the favored limits of carbonate deposition.

Thus in geological history there will be oscillations between times of carbonate and non-carbonate deposition. With sub-cycles within the cycles and finer stratigraphic subdivisions there will be every stage of transition between the two extremes. The effect on the sediments themselves will be apparent from a study of the micro-facies (Fairbridge, 1954). The smallest oscillations of sea-level should ultimately be detectable from a detailed study of the carbonates. The value of such micro-changes as a tool in stratigraphic correlation need hardly be stressed, and, in the "global thinking" of oil exploration men, even long-distance, inter-continental correlation will at times be possible.

Modern Carbonate Environments

Both the pelagic and biohermal classes of sediment may be largely of carbonate materials, while the terrigenous and volcanic components are often admixed with smaller quantities of carbonates. Modern carbonate environments thus extend over a very great range of bathymetry; in great depths however, the carbonates are eliminated completely, unless introduced by gravitational slumps or turbidity currents and quickly buried.

Studies of marine carbonates are showing that they are essentially biogenic in origin, that is to say, they consist of the exo-skeletons or other hard parts of marine organisms and plants, either whole or in clastic form. Since the finer clastics grade down to clay-size particles, they have been difficult to identify in the past, and this led to the theory put forward by Arnold Heim and others, about twenty to thirty years ago, that the bulk of marine carbonates, past and present, are chemical precipitates (essentially "drewite").

However, with the development of X-ray analysis and other techniques, there is now a reversion to the ideas of the last century (Sorby and others), that most marine carbonates are, in fact, biogenic. Even in the type localities of "drewite", Florida Bay and the Bahama Banks, the occurrence of inorganic aragonite in regular acicular crystals is found to be much less common than previously believed. The strictly chemical precipitation of aragonite in these specialized environments may be brought about by extreme conditions of high pH, super-saturation and "seeding", but even this process, too, may in part be biochemical.

We thus recognize two main environments of carbonate sedimentation today, distinguished primarily on a basis of bathymetry (i.e. depth).

(a) *BATHYAL and ABYSSAL REGIONS*: these are essentially the lower parts of the continental slopes and the marine basins or troughs that reach from 100-500 fathoms down to about 3,000 fathoms. Below such depths solution of carbonate sediments due to high CO_2 pressure is the usual experience (see Sverdrup *et al.*, 1942), but near the steeper slopes anomalous distribution may occur as the result of gravitational slides, and from rapid redistribution and burial due to turbidity currents.

At such depths there is a complete absence of light (the "aphotic zone") and there is no calcareous benthonic flora; even the benthonic fauna is restricted and makes very little contribution to the bulk of the sediment. This is the region of pelagic sedimentation and the organic oozes; the principal facies are globigerina, pteropod, coccolith and rhabdolith oozes in the warmer latitudes (approximately 40° N. and S.). In the colder latitudes their place is largely taken by the siliceous oozes. Bottom temperatures are rather uniform at such depths, right through from the tropics to polar regions: thus about 1°C. near the bottom, increasing slightly on the very floor (due mainly to heat flow from the earth's interior).

Bottom conditions within the bathyal and abyssal region vary considerably owing to contrasting conditions of ventilation or oxidation. Well aerated, open basin conditions lead to the formation of white, chalk-like sediments. However, poorly ventilated basins result in the development of a reducing environment, low pH, and dark colors; anaerobic bacteria liberate H_2S, and iron sulfides are frequently present. Since $CaCO_3$ is known to be soluble in

H_2S, partial or complete break-down of pelagic carbonate shells is likely to take place. Occasionally a surface of a limestone bed in the Paleozoic is seen to have been corroded and etched prior to the deposition of the next bed; such may be a case of this bottom acidification under low pH conditions. In the absence of aerobic decay bacteria, some of these barred basins muds become dominantly carbonaceous or sapropel oozes.

It should be stressed that such poorly ventilated basins are frequently not barred, in the sense of having an emergent barrier, but rather possess a sill that prevents free mixing with the general oceanic circulation; such a sill or ridge may, for example, occur at 100 fathoms, cutting off a 1,000 fathom basin from the main ocean body.

(b) *NERITIC SHELVES AND PLATFORMS*: In these shallow environments the depths range from 0-100 fathoms, exceptionally to 500 fathoms. In the latitudes where carbonate deposition is favored, the temperatures are essentially warm (say 10-30°C., or 50-86°F.) and the supply of light and foodstuffs reach their maximum. Such regions are marked by tremendous organic activity since rates of metabolism and reproduction are at their highest. These environments are suited especially to biohermal and biostromal development, which in turn leads to the formation of wave- and biologically reduced clastics.

The writer proposes that such sediments may be called the "biohermal suite". The term "bioherm" was originally proposed by Cumings and Shrock (1928) for any massive biogenic structure growing on the sea-floor; it is important to distinguish from this concept the term "reef", which by definition (see Webster's Dictionary) means a rocky structure of under 6 fathoms that causes waves to break. Obviously if waves break over a reef-forming bioherm, there will be an accumulation of clastic debris. On the other hand, many bioherms do not anywhere near reach the surface and consequently do not cause waves to break. Thus they are not associated with a peripheral ring of clastics; the importance of this difference in the search for porous reservoirs need hardly be stressed.

The expression "biohermal suite", "complex", "association" or "assemblage", thus connotes, not only the massive reef-like structures, but also non-reef forming bioherms and biostromes and all the *carbonate clastics,* precipitates and their derivatives which are spread out by waves and currents, or transported bodily by submarine landslides; the latter in turn are likely to set up a turbulent flurry of finer sediment that may well form a turbidity flow that may carry some of these reef-derived carbonates far out into a basin.

In the partially protected lagoons of an organic reef, a favorable environment will be created for the formation of such mechanico-chemical sediments as *oolites,* the nuclei of which are often biogenic. Large quantities of coarse biogenic clastics are washed up on to beaches, and, thanks to solution and reprecipitation in the intertidal belt, tend to become cemented in situ within a few months as *beach rock.* Supersaturated lime-rich sea-water splashed onto the shore also precipitates as "pelagosite" (described by Tschermak in 1878). Loose biogenic lime sand near the upper limit of tide and swash tends to dry out and is blown up to form dunes; these, being calcareous, become cemented within a few thousand years to form *calcareous eolianites* (or "eolian calcarenites").

Diagenesis in the lagoon and in other submerged deposits is slower, but the inversion of aragonite to calcite begins quite soon after burial. Thus in the Funafuti and Australian Barrier Reef bores it is found that the aragonite content (initially very high) drops away sharply with depth and at about one hundred feet (representing, say five or ten thousand years) has practically all reverted to stable calcite (Fairbridge, 1950). Carbon-14 studies, now in hand, may soon provide an exact figure for the rate of this change.

The Role of Magnesium in Organic Carbonates

In his studies of carbonate shells, Bøggild (1930) found that magnesium carbonate was often found in solid solution within the crystal lattice of calcite. In fact, very little magnesium carbonate is found in the marine realm in any other form. $CaCO_3$ has a polymorphic crystal habit, and the crystal form dictates its ability to take up magnesium, and also traces of strontium, barium and lead. Bøggild noticed that in shells the magnesium occurred in three ways; and Chave (1954) has given the detailed analyses, expressed approximately as follows:—

(i) low-magnesium aragonite (under 1%)
(ii) low-magnesium calcite (1-2%)
(iii) high-magnesium calcite (10-15%)

Furthermore, Chave has shown that the ability of calcite to take up magnesium is related inversely to the level on the evolutionary tree that the animal or plant concerned has reached: thus foraminifera and calcareous algae run high in magnesium, mollusca and arthopods run low. In addition, within any class the environmental temperature of the organism also affects the figures: the higher the temperature of the sea-water, the higher the magnesium component.

This discovery has a profound significance. It means that certain carbonate sediments from shallow warm environments are likely to be initially very high in magnesium, others very low. They could alternate in fact, with oscillating climatic cycles, or with rise or fall of sea-level.

Magnesium in Diagnosis

The most significant property of both aragonite and high-magnesium calcite is that they are unstable (Jamieson, 1953); that is to say they are both liable to break down and invert to low-magnesium calcite. The aragonite inversion takes place faster than the break down of the high-magnesium calcite. Both may go into solution, in an ionic state, in the abundant connate (i.e. originally sea-) water in their pore spaces.

Normally sea-water is not saturated in magnesium ions. But under special conditions, such as a reducing environment, ammonia salts, a high Ph, and particular thermodynamic conditions (temperature and pressure), but not necessarily all at once, magnesium will reach saturation along with calcium (Irving, 1926). Since the double carbonate, dolomite, is denser than either of the single carbonates, confining or shearing pressures will favor the formation of dolomite.

Only a small amount of dolomite may be accounted for by this method, owing to limited supply of magnesium-rich calcite, even in fairly rich sediments, such as algal limestones. However, it seems likely that once the metasomatic process is initiated and dolomite nuclei develop, further precipitation

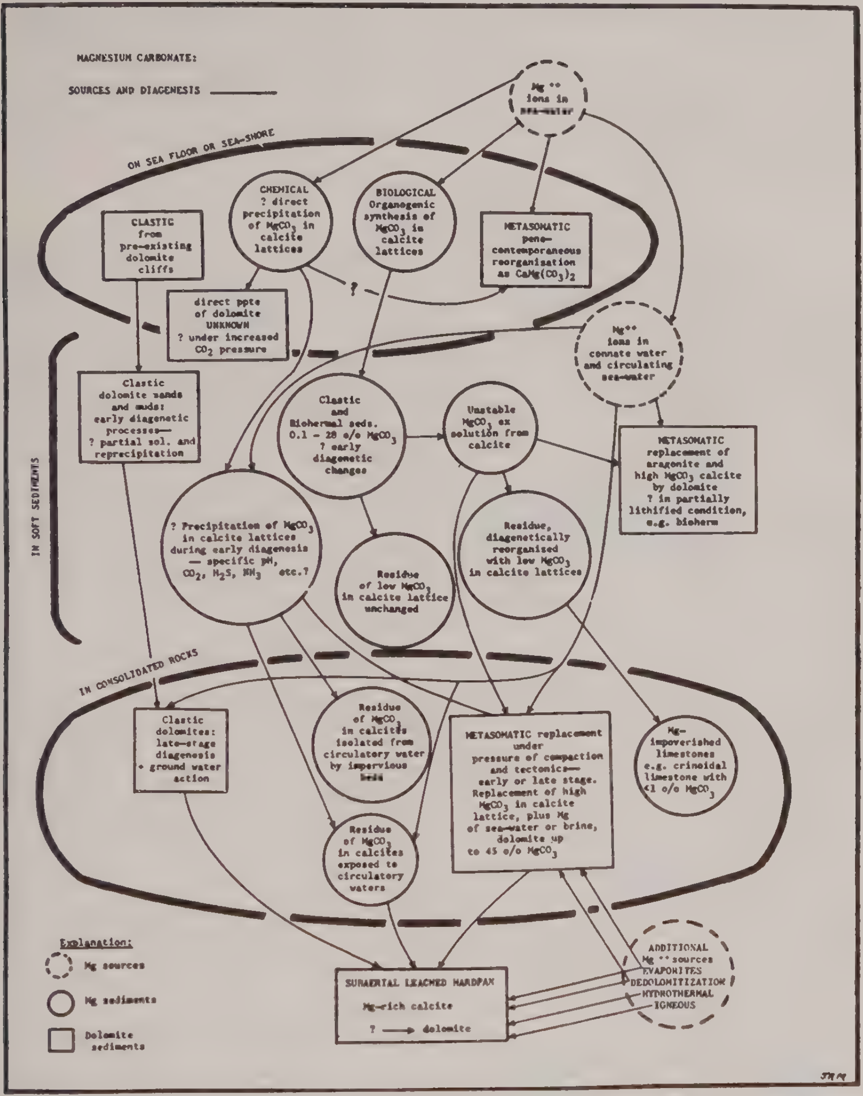
MAGNESIUM CARBONATE:
SOURCES AND DIAGENESIS
Mg^{++} ions in sea-water
ON SEA FLOOR OR SEA-SHORE
CLASTIC from pre-existing dolomite cliffs
CHEMICAL ? direct precipitation of $MgCO_3$ in calcite lattices
BIOLOGICAL Organogenic synthesis of $MgCO_3$ in calcite lattices
METASOMATIC pene-contemporaneous reorganisation as $CaMg(CO_3)_2$
?
direct ppte of dolomite UNKNOWN ? under increased CO_2 pressure
Mg^{++} ions in connate water and circulating sea-water
IN SOFT SEDIMENTS
Clastic dolomite sands and muds: early diagenetic processes— ? partial sol. and reprecipitation
Clastic and Biohermal seds. 0.1 - 28 o/o $MgCO_3$? early diagenetic changes
Unstable $MgCO_3$ ex solution from calcite
METASOMATIC replacement of aragonite and high $MgCO_3$ calcite by dolomite ? in partially lithified condition, e.g. bioherm
? Precipitation of $MgCO_3$ in calcite lattices during early diagenesis — specific pH, CO_2, H_2S, NH_3 etc.?
Residue of low $MgCO_3$ in calcite lattice unchanged
Residue, diagenetically reorganised with low $MgCO_3$ in calcite lattices
IN CONSOLIDATED ROCKS
Clastic dolomites: late-stage diagenesis + ground water action
Residue of $MgCO_3$ in calcites isolated from circulatory water by impervious beds
METASOMATIC replacement under pressure of compaction and tectonics— early or late stage. Replacement of high $MgCO_3$ in calcite lattice, plus Mg of sea-water or brine, dolomite up to 45 o/o $MgCO_3$
Mg-impoverished limestones e.g. crinoidal limestone with <1 o/o $MgCO_3$
Residue of $MgCO_3$ in calcites exposed to circulatory waters
Explanation:
Mg sources
Mg sediments
Dolomite sediments
SUBAERIAL LEACHED HARDPAN
Mg-rich calcite
? → dolomite
ADDITIONAL Mg^{++} sources
EVAPORITES
DEDOLOMITIZATION
HYDROTHERMAL
IGNEOUS
JRM

FIGURE 2

Diagram illustrating the possible sources of marine magnesium carbonate, and its subsequent diagenetic history. Four environmental stages are envisaged; on the shallow sea floor or seashore, in soft recently deposited sediments, in consolidated rocks before, during or after orogeny, and finally in or near the land surface under sub-aerial or ground-water conditions. Note that a number of theoretical alternatives are indicated with a "?". For most of these there is certainly very little evidence, but they have been introduced in order to test the data.

will take place from calcium and magnesium-saturated connate water, that is fed either initially from the ocean (the basements of coral reefs are notoriously porous), or from artesian movement. The shearing pressure instituted by the build-up and gravitative collapse tendency of a giant atoll cone would seem to explain the dolomites at over 638 feet in the Funafuti Atoll bore, and regional tectonic pressures may help to explain some of the mid-continent Paleozoic dolomites.

Conclusion

The writer mentions these suggestions with diffidence, because laboratory investigations are sorely needed, but at least they may provide a stimulus to those equipped with the necessary facilities. As regards carbonates in general, the writer again would like to stress the need for research into modern carbonates that are forming in the shallow oceans of today. These are also regions of considerable entrapment of organic material, which should be stimulus enough for oil men aware of the organic development of petroleum.

Acknowledgments

Warmest appreciation is due to the many geologists who have assisted the writer in discussion and criticism of some of the ideas expressed above, notably R. R. Revelle, Keith E. Chave, C. Teichert, F. R. S. Henson, and P. H. Kuenen; also to draftsman J. R. Moriarty for kind assistance with the diagrams.

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(*Reprinted from Nature, Vol.* 175, *p.* 1086, *June* 18, 1955)
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Some Unusual Carotenoids from Two Nudibranch Slugs and a Lamprid Fish*

RECENTLY, it has been possible to examine briefly some rare carotenoids of three conspicuously pigmented animals found in the waters off southern California.

Archidoris montereyensis, the sea lemon, is a nudibranch of generally light, slightly dirty yellow colour, with small scattered brown, greyish or black skin-spots and a pair of elongated, finger-like, pointed rhinophore tentacles. Two whole specimens were finely comminuted under acetone in a Waring blendor, and the yellow pigment was transferred from the separated solvent into light petroleum by dilution with water. In the partition test with 90 per cent methanol, all the pigment remained epiphasic, that is, in the petroleum, even following treatment with alcoholic potash. Its absorption spectrum was very similar to that of β-carotene. On chromatography, using activated alumina, a minor fraction (about 5 per

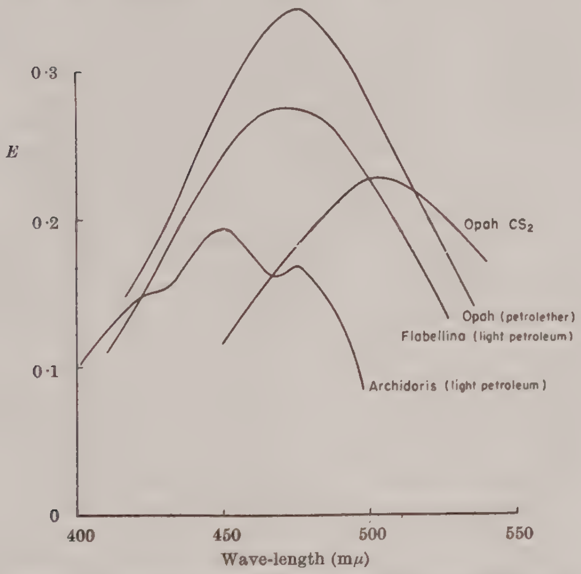

Fig. 1. Absorption spectra of the carotenoid pigments obtained from *Archidoris montereyensis*, *Flabellina iodinea* and *Lampris regius* (the opah or moonfish)

cent of the total) was eluted with light petroleum containing 5 per cent ether, and appeared to be β-carotene, while the major compound migrated downward when more ether (10–20 per cent) was added to the light petroleum. The absorption spectrum of this major fraction showed maxima at 475 mμ, 450 mμ and an inflexion at about 425 mμ (Fig. 1; Beckman photoelectric spectrophotometer, Model *DU*), thus differing slightly from β-carotene, from an authentic sample of which it could also be separated chromatographically. Although adsorbed more firmly on alumina than β-carotene, it adhered less strongly than cryptoxanthin (3-hydroxy-β-carotene). It appears rather similar to an unidentified pigment observed in human blood and milk[1] and in berries of *Lonicera japonica*[2].

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* Contribution from the Scripps Institution of Oceanography, New Series No. 772.

The finding of only hydrocarbon-like (persistently epiphasic) carotenoids in a marine mollusc seems to be almost unique, since these animals are generally characterized by solely or predominantly hypophasic carotenoids[3]. The deep rose-pink nudibranch, *Hopkinsia rosacea*, yields no carotenes or esterified xanthophylls, but a new xanthophyll with absorption maxima at 497 mμ and 466 mμ in petroleum ether, believed by Strain[4] to be a ketone.

Flabellina iodinea, the purple sea-slug occurring commonly off La Jolla, has bright purple-violet or purple-blue body skin, orange-red rhinophores and orange-coloured cerata. Two specimens extracted in the same manner as was *Archidoris* yielded a hypophasic carotenoid showing a single, symmetrical absorption maximum at 470–475 mμ in petrol ether (Fig. 1). This type of spectrum suggests that the pigment may be an oxygenated carotenoid, possibly of ketonic nature; it is not, however, of the astaxanthin class, since it exhibited no acidogenic properties after treatment with ethanolic potash. The fact that the purple colour of *Flabellina* changes to red-orange upon treatment with alcohol suggests the presence of a carotenoid protein complex, common in many invertebrates.

Lampris regius. The opah or moonfish, a large oceanic species showing a roundish dorso-ventral profile, with compressed sides, has a brilliant red pigment in the skin, fins, lips and tongue. The specimen examined was taken on a baited hook and long line at a depth of some forty fathoms, approximately four hundred miles west of Magdalena Bay, Baja California. It and other similarly caught specimens contained a few fish and many argonaut cephalopods in the stomach.

The red pigment, recoverable from any of the tissues mentioned above, is somewhat similar to that obtained from *Flabellina*, being persistently non-acidogenic, although exhibiting a symmetrical, single-banded absorption spectrum, with a maximum at 475 mμ in petrol ether, and at 504 mμ in carbon disulphide (Fig. 1). This is somewhat reminiscent of a neutral xanthophyll recovered by Lederer[5] from freshwater perch (*Perca fluviatilis*) in that that compound gave a single maximum at 495 mμ in petrol ether and 510 mμ in carbon disulphide.

The opah does not store the crustacean carotenoid, astaxanthin, but may obtain its carotenoid, deriving ultimately from such a source, through its heavy diet of argonauts.

We wish to acknowledge with thanks the generosity of Mr. John A. McGowan for the nudibranchs collected by him, and of Mr. Allan J. Stover and Prof. Carl L. Hubbs for the opah material and information concerning the species. Thanks are also due to the Rockefeller Foundation for financial assistance.

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[1] Kon, S. K., and Mawson, E. H., Spec. Rep. Ser. Med. Res. Coun. Lond., No. 269 (1950).

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Printed in Great Britain by Fisher, Knight & Co., Ltd., St. Albans.

Separatum
EXPERIENTIA
BIRKHÄUSER VERLAG, BASEL, SCHWEIZ

Vol. XI/7, 1955 – p. 270

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Some Observations on Pigments of the Pacific Sand Dollars, *Dendraster excentricus* and *Dentraster laevis*[1]

Two of the commoner flat echinoid species of the Pacific coast are the purple sand dollar, *Dendraster excentricus*, and its light tan or buff-coloured, smooth-surfaced relative, *D. laevis*, which possesses fewer, shorter, slenderer spines and which inhabits deeper, colder water (CLARK[2]). The animals live on sandy floors, often burying or half-burying themselves therein. They are typical feeders on sandy detritus.

Collections of each species were made by the diving instructor, Mr. CONRAD LIMBAUGH, on July 20–21, 1954, *Dendraster excentricus* being taken from a depth of about 6 fathoms beneath the surface in the New Valley of Scripps Submarine Canyon, and *D. laevis* from depths of 8–11 fathoms, on the floor of the La Jolla Submarine Canyon.

In addition to the relatively minor morphological differences between the two species, the obvious differences in their colours and in their respective habitats, there is a striking biochemical contrast which led to this investigation. When preserved in dilute formaldehyde solution, each species readily yielded its own characteristic pigment, the purple animals conferring a deep port-wine purple, and the buff ones, a conspicuous green colour to the aqueous solution, while the whole external surfaces of the latter animals changed from light buff to deep green in colour. A similar discharge of pigment occurs in distilled water.

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[1] Contribution from the Scripps Institution of Oceanography, University of California, New Series No 773.

[2] H. L. CLARK, Allan Hancock Found. Publ., First Series Allan Hancock Pacific Expedition *8*, 225 (1948).

An earlier report briefly mentioned the presence of echinochrome in the ectoderm, endoderm, intestine, ovary, spermary and egg cases of *Dendraster excentricus* (Fox and SCHEER[1]). In the present study, two or more such fractions were recognized, and will be discussed below.

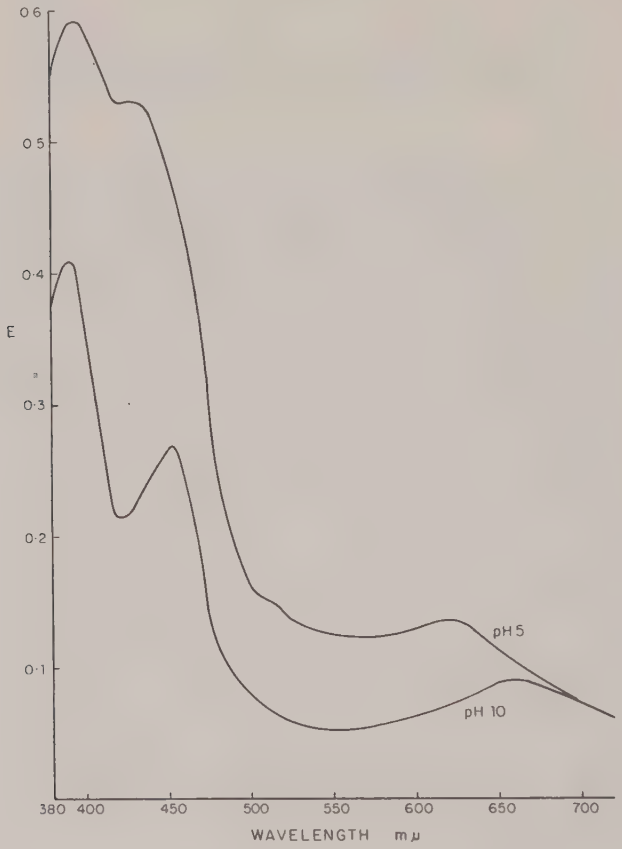

Fig. 1.–The absorption spectrum of the water-soluble pigments from *Dendraster laevis*. (*A*) at pH 5·0; (*B*) at pH 10·0.

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[1] D. L. Fox and B. T. SCHEER, Biol. Bull. Woods Hole *80*, 441 (1941).

(354)

Dendraster laevis. This species often exhibits small green patches or scars when first collected. The effect may be replicated quickly by rubbing or scraping the animal's surface to rupture the ectoderm, which at once turns green, while the pigment is readily liberated into sea water. The whole internal organs yield the green pigment into distilled water, just as does the whole intact animal.

In the leaching of the pigment by distilled water, the prevailing pH (5) is not the controlling factor, since sea water adjusted to the same pH value leached no pigment even after an overnight period; the animals remained alive. The pH had risen, however, after a few hours, to 5·8.

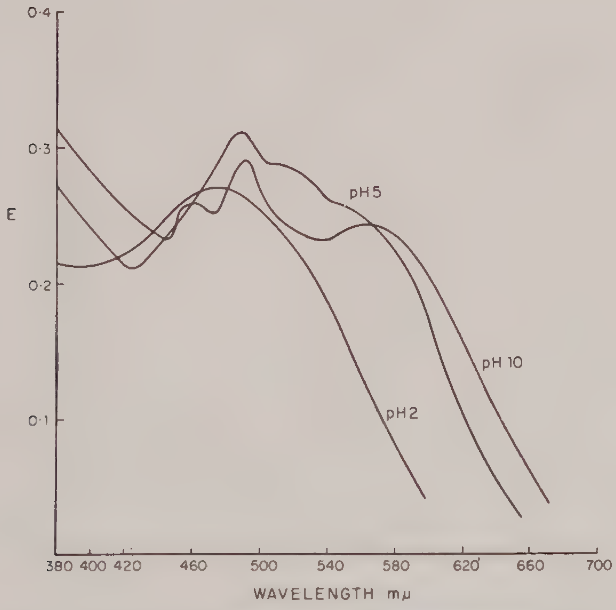

Fig. 2.–The absorption spectrum of the water-soluble pigments from *Dendraster excentricus.* (*A*) at pH 2; (*B*) at pH 5; (*C*) at pH 10.

Sea water containing 10% (v/v) of concentrated formaldehyde produces the colour change to green only very slowly, and without evident leaching.

The green pigment is not soluble in ether or in chloroform; it loses its colour at pH values below about 3 (dilute acetic acid), turns green at about pH 5; above pH 10·0 it is precipitated in murky green flocs. The maxima at pH 5 are at 395, 430, (510), and 620 mμ, and at pH 10, 395, 455 and 660 mμ (Fig. 1).

The addition of very small amounts of hydrosulphite produces no obvious effects; somewhat more of the salt causes a discharge of the colour, due to pH effects, since some of the colour may be restored, not by shaking in air but by neutralizing with bicarbonate.

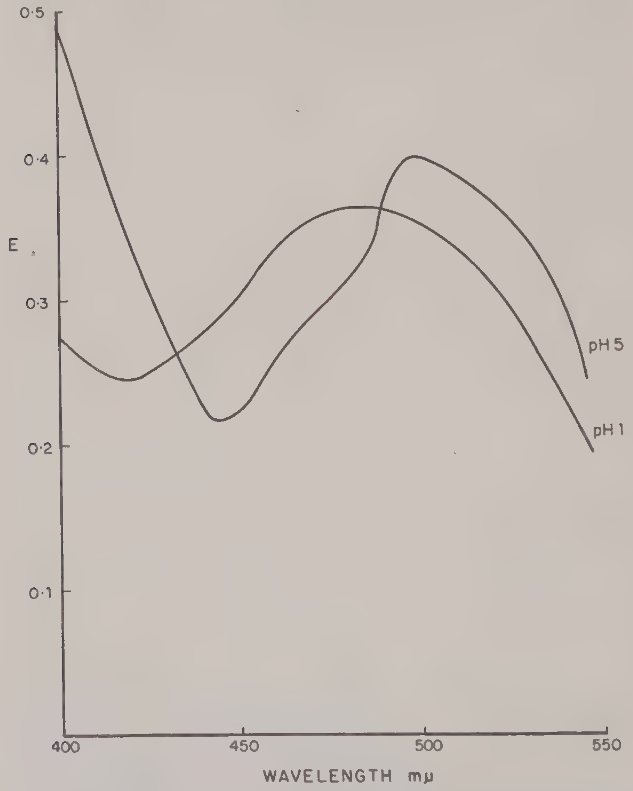

Fig. 3.–The absorption spectra of the least adsorbed pigment fraction from the water-soluble purple pigments of *Dendraster excentricus*. (i) at pH 1; (ii) at pH 5.

When the shell of *D. laevis* is treated with HCl and ethyl ether (Goodwin and Srisukh[1]) no pigment passes into the ether as the skeleton dissolves, indicating the absence of any echinochrome-like naphthoquinone pigments.

Dendraster excentricus. The water-soluble purple pigment of this species turns orange-red at pH 1 and is precipitated as a brownish mass at pH 10. Absorption maxima of aqueous systems at different pH values are shown in figure 2.

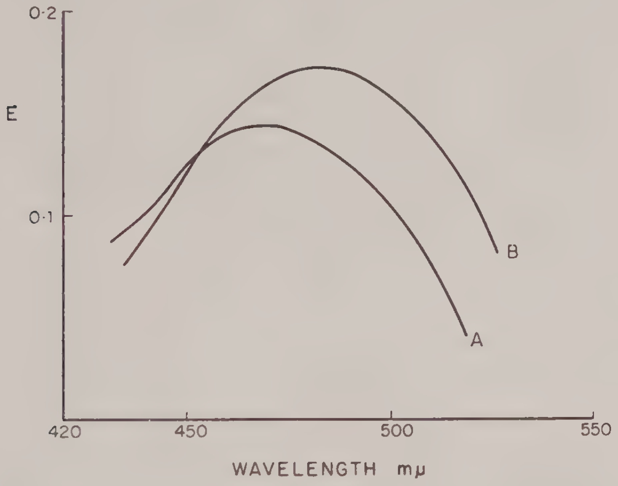

Fig. 4.–The absorption spectra in ether of the two main "echinochrome-like" pigments from *Dendraster excentricus*. (*A*) the less strongly adsorbed pigment; (*B*) the strongly adsorbed pigment.

The pigment passed uninterruptedly through a celite column, but was adsorbed by alumina, from which 10% HCl removed an orange-purple fraction (*A*) whilst a firmly bound purple component (*B*) remained at the top of the column.

The colour changes in fraction *A*, according to prevailing pH (Fig. 3), suggest that the firmly adsorbed purple fraction *B*, not yet isolated in pure form, may be mainly responsible for the prominent peak at 480 mμ, observed in the crude extracts (Fig.2). These pigments are not extractable with ether, but are reversibly reducible with hydrosulphite, which suggests a quinonoid character.

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[1] T. W. Goodwin and S. Srisukh, Biochem. J. *47*, 69 (1950).

Treating the shells of *D. excentricus* with HCl and ether yields an orange ethereal extract, indicating the presence of echinochrome-like pigments (cf. Fox and Scheer[1]). Chromatography on $CaCO_3$ yields two main fractions, although there are small traces of others as well. Fraction *A*, eluted with ether, exhibits a rather broad absorption maximum at 470 mμ; and *B*, eluted with ethanol, a maximum of similar shape at 485 mμ (Fig. 4). Both pigments are extractable from etheral solution with soda, and both are reversibly reducible with hydrosulphite. They do not appear to be any of the quinonoid pigments already described by Lederer[2].

Thus the two species of *Dendraster* are in contrast through their pigments, as summarized in the table. The state of the water-soluble pigments in the tissues has not yet been investigated. The green pigment of *D. laevis* is normally present in its colourless form.

A Comparison of the Pigments of *Dendraster excentricus* and *D. laevis*

Pigment	*D. laevis*	*D. excentricus*
Water-soluble	Green; colourless below pH 5·0	Two pigments, purple above pH 5·0, orange-purple below pH 5·0
Ether-soluble	absent	Two echinochrome-like pigments present

Nutritional or metabolic differences between the two species, as emphasized by these marked pigmentary contrasts, would be well worth detailed study.

T. W. Goodwin and D. L. Fox

Department of Biochemistry, The University of Liverpool, England, and Division of Marine Biochemistry, Scripps Institution of Oceanography, University of California, La Jolla, California, March 27, 1955.

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[1] D. L. Fox and B. T. Scheer, Biol. Bull. Woods Hole *80*, 441 (1941).

[2] E. Lederer, Biochem. Biophys. Acta *9*, 92 (1952).

(358)

Zusammenfassung

Dendraster laevis bildet ein grünes, wasserlösliches Pigment (farblos bei pH unter 5) und kein Echinochrom. *Dendraster excentricus* dagegen erzeugt zwei purpurrote, wasserlösliche und zwei echinochromähnliche Pigmente.

T.W. Goodwin
Denis L. Fox

(*Reprinted from Nature, Vol.* 175, *p.* 942, *May* 28, 1955)

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Astaxanthin in the American Flamingo[*]

THE flamingo, *Phoenicopterus ruber*, derives from its dietary carotenoids the conspicuous rich pink to red colours of its feathers, tarsal and pedal skin and lower bill-mandible. Captive flamingos gradually lose their rich pigmentation unless appropriate dietary measures are taken. The presumptive role of crustacean carotenoids in supplying pigmentation to the birds in Nature is given some support by observations in zoos[1] and by Manunta's[2] reported recovery of an astacene-like carotenoid from the fat of a flamingo.

In the San Diego Zoo, a flock of two dozen flamingos has received, since March 1954, finely ground carapace (plus some hypoderm) of the California 'spiny lobster', *Panulirus interruptus*, added as a regular supplement to the usual diet of beef- or horse-liver, grass-pellets, millet, wheat, rice, dried flies and ground shrimp. As a result, the American species, *Phoenicopterus ruber*, soon developed striking pink and vermilion colours in the skin (not in the transparent scales) of the tarsals, heel and webbed toes, the lower mandible and the new plumes. Three members of a smaller species, the Chilean flamingo (*P. chilensis*), exhibit bright pink skin over their heels and webbed feet, but not elsewhere; their feathers remain mostly white as in Nature, but now with a few pink ones. The rest of the general body-skin is of normal, pale appearance (like that of domestic fowls) in both species.

Although the birds receive mixed carotenoids in their diet (notably since they pluck grass as well), the various tissues yield chiefly hypophasic carotenoids, and the majority of these seem to be partially oxidized xanthophylls, their chromatographic fractions giving atypical spectral absorption curves. The minor amounts of epiphasic carotenoids include no typical carotenes, but apparently oxidation products of carotenes.

No traces of astaxanthin, or of any acidogenic carotenoid, were detected among the carotenoids of the yellow-orange sub-dermal or visceral fat, the orange adrenals, the liver, pancreas, spleen, lung, muscle, immature ovary or testes of recently expired birds which had received the regular diet. Nor did the carotenoid-rich plasma of blood yield astaxanthin. The erythrocytes contained no carotenoids. Even the blood-laden shafts of pin feathers, while rich in carotenoids, yielded no trace of the acidogenic carotenoid save for a possible trace in one sample. No carotenoids were recovered from the pale, semi-fluid contents of small or large intestine.

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[*] Contribution from the Scripps Institution of Oceanography, University of California, New Series No. 774.

However, the bright pink feather barbs themselves, as well as the brilliant vermilion skin underlying the tarsal scales, yielded copious amounts of astaxanthin as a prominent fraction of the carotenoid complement. The identity of the astaxanthin was established both by the single broad maximum of its oxidized derivative, astacene, at 495–496 mμ in pyridine, matching that of astacene from *Panulirus* and other crustaceans (Beckman *DU* photoelectric spectrophotometer), and by mixed chromatography of the astacene derivative from skin, from feathers and from *Panulirus*. Each chromatogram alone, and the mixture of the three, appeared to be identical on columns of magnesium oxide and 'Celite'.

Hydrolysed feathers yielded no epiphasic carotenoids, but only astacene and neutral hypophasic derivatives. The skin provided three or more neutral xanthophylls of unfamiliar spectra, two minor atypical, persistently epiphasic fractions, and considerable amounts of astaxanthin.

A roseate spoonbill (*Ajaia ajaja*), receiving the same diet as the flamingoes, grew pink feathers which, after alkaline hydrolysis, yielded astacene as the predominant, if not the only, carotenoid.

The metabolic fractionation of dietary carotenoids by the American flamingo seems to involve oxidative processes as well as partial transfer of unchanged astaxanthin to the integument. A remaining puzzle involves questions as to (1) the enzymic astaxanthin-oxidizing agency, if any, residing in the gut or in the blood, which must, nevertheless, undoubtedly transport astaxanthin to the tarsal skin and plume follicles, and (2) the rate of destruction of astaxanthin en route. Experimentation continues as opportunity permits, and a full report will be published elsewhere.

I thank the following for their interest, co-operation and technical aid: at the Scripps Institution, Dr. Arthur L. Kelly, Mr. E. F. Corcoran and Mr. Elmer Squier, research assistants; at the San Diego Zoo, Dr. Charles R. Schroeder, director; Mr. K. C. Lint, curator of birds; Mr. Merl Moody, manager of the food warehouse; and my late son, Stephen, university student and summer-time assistant keeper in the bird-yard, who was accidentally killed on July 15, 1954.

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Division of Biochemistry,
Scripps Institution of Oceanography,
University of California,
La Jolla, California. Jan. 4.

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Printed in Great Britain by Fisher, Knight & Co., Ltd., St. Albans.

Geol. Soc. America
p. 237–254, 9 figs., 1 pl.

Special Paper 62, 1955
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Tonga Trench*

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ABSTRACT

During the Capricorn Expedition of 1952–1953 the research vessels HORIZON and SPENCER F. BAIRD spent two weeks in the Tonga Trench and Archipelago making echo-sounding, coring, seismic-refraction and towed-magnetometer studies.

The Tonga Trench is a slightly arcuate furrow convex to the east over most of its length. Between Tafahi and Samoa it bends sharply to the northwest, appearing to follow the andesite line. It is continuous at depths greater than 7000 m for 1100 km, including in this segment three elongate basins deeper than 9000 m and one deeper than 10,000 m. The deepest basin explored lies at about 23° 15′ S., near a sharp bend in the axial trend, where bomb sounding gave a depth of 10,800 ± 200 m. A typical west-to-east profile, 350 km long, across the central Tonga Islands, crosses a chain of active volcanic islands at Kao, crosses the narrow Tofua Trough of 1700 m depth to the coralline island Lifuka, then down the west flank of the trench to a maximum depth of 9000 m in a steep-walled gorge 1–5 km wide. The east flank rises more gently to a broad ridge rising about 350 m above the general level of the sea bottom eastward. At 26° 00′ S. Lat. and at 18° 45′ S. Lat. the trench is constricted by large seamounts on the east flank. The latter seamount caps a smooth rise from 7500 m to 410 m and appears to be a guyot tilted westward.

Scattered bottom samples indicate that, except for the calcareous deposits found on the main Tongan ridge, the sea floor in the area is largely volcanic sand and gravel, probably ejected from the near-by active volcanoes.

Seismic-refraction profiles, parallel to the axis of the trench, indicate that the sediment foundation throughout the area is a rock, probably volcanic, of compressional wave velocity 5.2 ± 0.2 km/sec. The sediment thickness is about 2 km in the Tofua Trough, very thin, <200 m on the average, in the inner gorge of the trench, and about 400 m on the east flank, 50 km from the trench axis. Beneath the 5.2 km/sec basement the crustal velocity is 7 km/sec in Tofua Trough, 6½ km/sec at the trench axis and also on the east flank.

The Mohorovičić discontinuity, characterized by a velocity of 8.1 ± 0.1 km/sec, is estimated to be at a depth of 20 km below sea level at the trench axis, and 12 km below sea level on the east flank. This velocity was not observed beneath Tofua Trough, where the highest velocity was 7.6 km/sec, estimated to occur at a depth of 12 km below sea level.

Two profiles of total magnetic field strength, recorded across the trench, have been used to estimate profiles of sediment thickness. When the effects of basement topography are eliminated, a deep-seated asymmetry remains that could indicate either that the Curie point isothermal surface is deeper or that the magnetic susceptibility is greater on the west side than on the east side of the trench.

INTRODUCTION

The Tonga Trench forms the northern portion of the Tonga-Kermadec Trench, which lies east of the Tonga and Kermadec islands and extends most of the distance

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* This is a contribution from the Scripps Institution of Oceanography, New Series, No. 775.

This work represents one of the results of research carried out under Contract NONR 23305, Office of Naval Research and Contract NObsr-43356, NE 120221-5 with the Bureau of Ships.

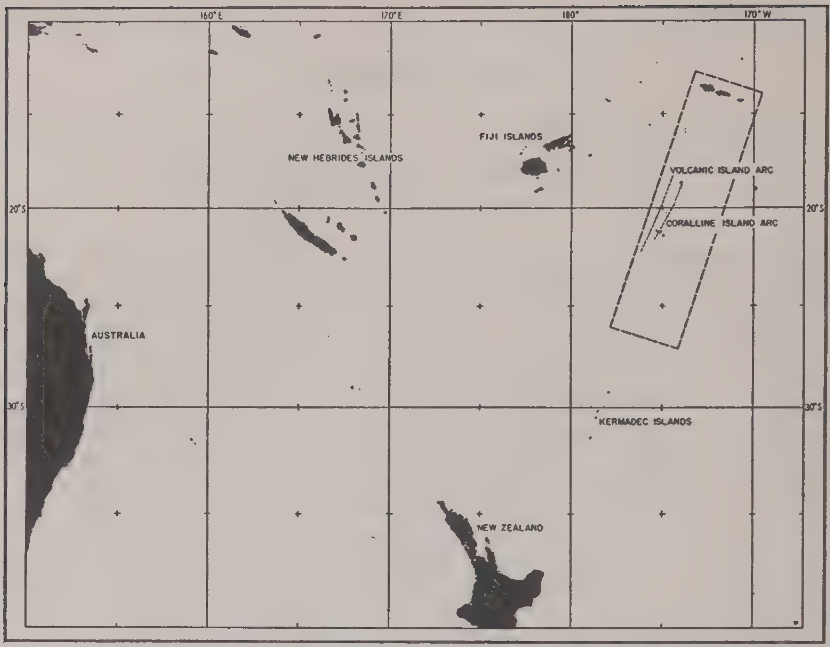

FIGURE 1.—*Index map*
The Tonga Islands region, within the dashed line, is shown in detail in Plate 1.

from New Zealand to Samoa. It forms a natural boundary dividing the spectacular Melanesian region, with its great variety of islands, basins, and submarine mountains, from the relatively deeper and less complex Pacific basin to the east. Its location relative to Australia, New Zealand, and eastern Melanesia is shown in Figure 1. Details of the Tonga Archipelago and Trench are shown in Plate 1.

The boundary separating volcanic rocks of continental type from those of Pacific type was called the andesite line (Marshall, 1911) and was drawn through the trench. Further study of Pacific rocks by MacDonald (1949) has supported this location.

The Tonga Trench region displays prominently all the features ascribed to Pacific arcuate structures (Gutenberg and Richter, 1949, p. 28, 48; Hess, 1948). These include, from east to west: (1) oceanic trench with associated shallow earthquake shocks; (2) line of volcanoes; (3) deep earthquakes concentrated in a fault zone dipping steeply away from the oceanic side of the trench. The earthquake sequence has been studied by Benioff (1949; 1954).

Although a great many of the early exploring expeditions visted Tonga and the existence of Tonga Trench has been known for at least 65 years there has been very little exploration of the area with modern techniques. Hecker made some gravity measurements of questionable accuracy (Gutenberg and Richter, 1949, p. 47–48), and some studies of crustal thickness have been made by using the dimension of surface waves from earthquakes received at Australia, New Zealand, and Samoa (de Jersey, 1946; Officer, 1954). Except for these measurements, knowledge of the structure was based entirely on scattered soundings inadequate to describe the exact form of the trench. Consequently, when the Capricorn Expedition of 1952–1953 of Scripps Institution of Oceanography passed through Tonga on a geological and geophysical reconnaissance of the South Pacific, about 2 weeks of its crowded schedule was devoted to exploration of the trench and associated environment.

ACKNOWLEDGMENTS

In gathering the great quantity and variety of data required in this study, the help of many people was necessary. This work was shared by all 31 members of the scientific party of Capricorn Expedition, and their help is gratefully acknowledged. An essential factor was the co-operation of the officers and crews of the research vessels HORIZON and SPENCER F. BAIRD, who not only executed the difficult ship operations but also helped in the scientific work. The magnetic work was made possible by the co-operation of the Lamont Geological Observatory and the Geophysics Branch of the U. S. Geological Survey, which provided all the necessary equipment. Mr. Edward T. Miller of Lamont Geological Observatory gave much help and advice in the installation of the equipment.

Measurements of the seismic velocities of the Tafahi lava were generously supplied by Leon Knopoff of the Institute of Geophysics, University of California at Los Angeles.

PREVIOUS WORK

BATHYMETRY

The earliest systematic bathymetric observations in this area were made by H. M. Surveying Ship EGERIA, Pelham Aldrich and later C. F. Oldham commanding, during the years 1888–1890 (Admiralty Publications, 1889, p. 15–22; 1890, p. 5–7; 1891, p. 3). Nearly 300 wire soundings were made, mostly over the Tonga-Kermadec Ridge, but two soundings of over 7500 m were made in the southern portion of the Tonga Trench. In 1895 and 1898 H. M. Surveying Ship PENGUIN made wire soundings between New Zealand and Samoa and found depths of over 8500 m in the northern and central portions of the trench (Admiralty Publications, 1896, p. 3–6; 1899, p. 10). In 1899 the U.S. Fish Commission Steamer ALBATROSS, en route from Niue to Tongatabu, made two stations near the central part of the trench and trawled successfully at a depth of over 7600 m (Agassiz, 1903, p. 388).

With the advent of echo sounding, vessels in transit began reporting very deep soundings all along the east flank of the Tonga-Kermadec Ridge, but the validity of the positions and magnitude of many such soundings are doubtful. Such sounding lines definitely established that the trench curves westward sharply between Tafahi and the Samoa Islands. In 1952 the Danish oceanographic vessel GALATHEA made careful echo soundings nearly the entire length of the Tonga Trench and found depths approaching 10,000 m east of Tongatabu. In general the GALATHEA traverses follow the trench axis, so detailed cross sections cannot be constructed from her data.

GEOLOGICAL EXPLORATION OF THE ISLANDS

Summaries of the geology of the Tonga Islands are given by Reed (1921, p. 431–433) and Davis (1928, p. 242, 415–418), for example, but only Eua, an uplifted, terraced island at the southeast end of the group, has been examined in detail (Lister, 1891; Hoffmeister, 1932).

As Lister (1891, p. 591) noted, the Tonga Islands consist of three groups: (1) purely volcanic islands, (2) raised coralline islands, and (3) islands composed largely of volcanic sediments.

The volcanic islands form a western linear chain over 700 km long, from Ata (22° 20′ S.) to Tafahi (15° 51′ S.). Within this chain are such recently active volcanoes as Falcon Island (1885–1886, 1927; now submerged), Tofua (1906), Maurelle Island (1781), Late (1854), and Fonualei (1847), as well as several active submarine volcanoes. Kao, at 3380 feet, the highest peak of the chain, is dormant, but it is near the active caldera Tofua. A similar pair, the conical Tafahi and the near-by broad Niuatobutabu, lie isolated north of the main Tonga Islands but are connected to Fonualei by a ridge containing several shoals of less than 100 m depth. Insofar as known, eruptions from these volcanoes are andesitic. Harker (1891, p. 257) reports the rock from the 1885 eruption of Falcon Island as a basic augite andesite, while that of the 1927 eruption was a diabasic pyroclastic (Hoffmeister *et al.*, 1929). Tofua extruded augite andesite (reference not known). A hand specimen from Tafahi was obtained during the present investigation; under the hand lens it appears to be andesite with green (augite?) phenocrysts. Reefs are narrow or absent around these young volcanic islands.

The main Tonga Ridge, east of and parallel to the volcanic chain, is separated from the volcanoes by a trough or basin with a general depth of 1300–1700 m and a width of 25–35 km. Four limestone banks, from Tongatabn to the Vava'u group, 300 km to the north, are capped by low coralline islands, such as Lifuka or Nomuka, or pinnacles. The surface of these platforms slopes gently to the west; the banks are separated by narrow passages more than 500 m deep. Tongatabu, largest island of the Tonga group, has a maximum height of 270 feet and a gentle tilt to the northwest. Only calcareous material has been found on this raised atoll (?). The Vava'u group, with a maximum height of over 650 feet, shows in its three well-developed, southward-sloping terraces and elevated atoll rims evidence of major uplift (Davis, 1928, p. 983). However, the deep inlets and passages between banks, steep submarine slopes, and the drowned sea caves of Vava'u indicate that here subsidence is the dominant process at present.

Eua, geologically the best known of the Tonga Islands (Hoffmeister, 1932), represents the volcanic-sediment island with a veneer of calcareous material. It is the only island of the group where plutonic rocks, in this case boulders of norite, have been found. Eua has a complex geologic history, beginning, insofar as is known, with early or pre-Eocene volcanism and intrusion, which built the island core of nearly horizontally bedded water-laid tuffs and lava flows. This volcanism was followed, in the late Eocene, by the deposition in deep water of foraminiferal limestone, and in the Miocene (?) with more tuffs and marine deposits.

Intermittent uplift, chiefly in Pliocene time, formed several very well-developed reef-limestone terraces, with a present maximum height of more than 550 feet on the east side of Eua, while the older limestones, and exposed patches of the volcanic core, are now more than 1000 feet above sea level. As on the adjoining island of Tongatabu, the elevated reefs slope to the northwest.

Davis (1928, p. 483) decided that flexures associated with a migration eastward of the Tonga anticline might account for the tilted terraces and the changes of level indicated by the shallow-water topography of the Tonga Islands; then Eua would indicate the present position of the anticlinal crest, the westward-tilted banks would be west of the crest, and the belt of active volcanoes, with poor or missing reef borders, would stand on the sinking rear slope.

BOTTOM SAMPLES

Early surveying vessels obtained small bottom samples as a part of the sounding operation, by lowering a tallow or sounding tube on the sounding line. Their surveys were almost entirely in the shoaler areas, where calcareous fragments were taken on the coralline platforms and pumice or volcanic sand was found along the western island arc. Globigerina ooze, mixed with pyroclastic material, and volcanic muds were reported from the continental slope east of the Tonga Islands, and volcanic muds and sands between the island chains and west of the volcanic islands.

In 1899 the ALBATROSS dredged red clay at a depth of 5700 meters 120 km east of the trench axis, at 20° 15′ S., and (light-brown) red clay containing abundant volcanic glass, augite and plagioclase grains, and Radiolaria from about 7500 m on the east flank of the trench, 175 km east of Tongatabu (Agassiz, 1903, p. 388). In 1952 the GALATHEA cored a brown silty crystal tuff containing volcanic glass fragments and abundant augite and other ferromagnesian grains from nearly 10,000 m along the trench axis east of Tongatabu (Richard Y. Morita, personal communication).

TOPOGRAPHY

During the Capricorn Expedition the research vessels HORIZON and SPENCER F. BAIRD recorded more than 4400 miles of echo-sounding traverses near the Tonga Islands, including 24 crossings of the Tonga Trench.

Each ship was equipped with an EDO echo sounder modified to permit shoal-scale recording speed at the greatest depths. However, the HORIZON's echo sounder would not record suitably on the shoal scale at depths greater than 4000 fathoms; in such areas soundings were logged from audible returns checked against deep-scale recording or, at the greatest depths, by bomb soundings recorded by oscillograph. Input to each echo sounder was held at 60 cycles by a constant-frequency unit. Instrumental errors within the echo sounder were checked by comparing soundings as read with soundings determined from shots on the seismic runs. Soundings were recorded in fathoms, assuming a nominal sounding velocity of 4800 ft/sec. Deep hydrographic casts were made in the central portion of the trench to permit computation of sounding velocities based on the salinities and temperatures. Ships' positions were established by visual cuts on the islands or by star sights; the latter observations have a probable error of about 2 miles.

Plate 1 is a contoured plot of the sea-floor topography in the Tonga area, compiled from several sources, with depths expressed in meters. Along the Tonga Ridge, particularly south of Tongatabu, the topography is based chiefly on old wire soundings. North of Tongatabu, between the islands, echo soundings are more abundant, and positions, based on sights to the islands, are more dependable. The trench topography shown is based primarily on HORIZON-BAIRD data, supplemented by GALATHEA soundings near the trench axis. The echo soundings have been corrected for variation in sounding velocity with depth, with sounding velocities computed from Kuwahara's tables (1939). However, slope corrections have not been applied; echo distances to the nearest bottom have been calculated from travel times of first arrivals and plotted at the corresponding position of the ship. In shallow areas, or areas of gentle relief, the echo distance nearly equals the depth. At great depths and steep slopes, the echo distance is significantly less than the depth beneath the ship. The result is that the apparent width and depth of the deep, narrow regions are somewhat less than the true width and depth.

Some conclusions may be drawn from Plate 1:

(1) Detailed sounding shows that the Tonga Trench is an extremely narrow, slightly arcuate depression with a maximum width of 55 km at depths greater than 7000 m, whereas it is more than 1150 km long at such depths. At 9000 m the width is 3–7 km, but the trench is continuous at that depth for more than 700 km, including within the 9000 m contour three small basins and a knoll.

(2) The deepest portion of the trench sounded lies about 200 km south of Tongatabu, just north of a major change in trend of the axis. Here systematic bomb sounding gave a maximum echo distance of 10,635 ± 35 m, the deepest sounding recorded from the southern hemisphere (Fisher, 1954). Analysis of the echo trains recorded by oscillograph suggests, however, that the maximum depth here is 10,800 ± 200 m, not significantly different from the greatest depth yet reported, 10,860 m (5940 fathoms) from the Challenger Deep in the North Pacific (Gaskell, Swallow, and Richie, 1953, p 63).

(3) Where the trench is best developed, at depths of more than 6000 m, the west or shoreward flank of the trench is steeper, with slopes of 8°–15°, than the offshore flank, with general slopes of 3°–8°. In most cases the slope steepens with depth. Exceptions occur where seamounts constrict the trench on the east, at the latitude of Vava'u, and at 26°S. where a sill slightly shallower than 6000 m may separate the Tonga Trench from the Kermadec Trench to the south. Topography is less regular here than farther north in the Tonga Trench, but there is no evidence from this investigation to support an en echelon arrangement of these trenches.

(4) North of 17° S. the trench bends sharply to the northwest, ending rather abruptly between Tafahi and Savaii, westernmost of the Samoa group. At the north end, and similarly at the south end of the trench, the trench walls have more nearly equal slopes.

Figure 2 is a series of bathymetric profiles selected to illustrate differences in trench character along its length. Sections A-A′ and E-E′, at the north and south ends, respectively, resemble each other in having irregular, nearly equally sloping trench walls and minor peaks in the broad trench bottom. In addition, on profile A-A′ the

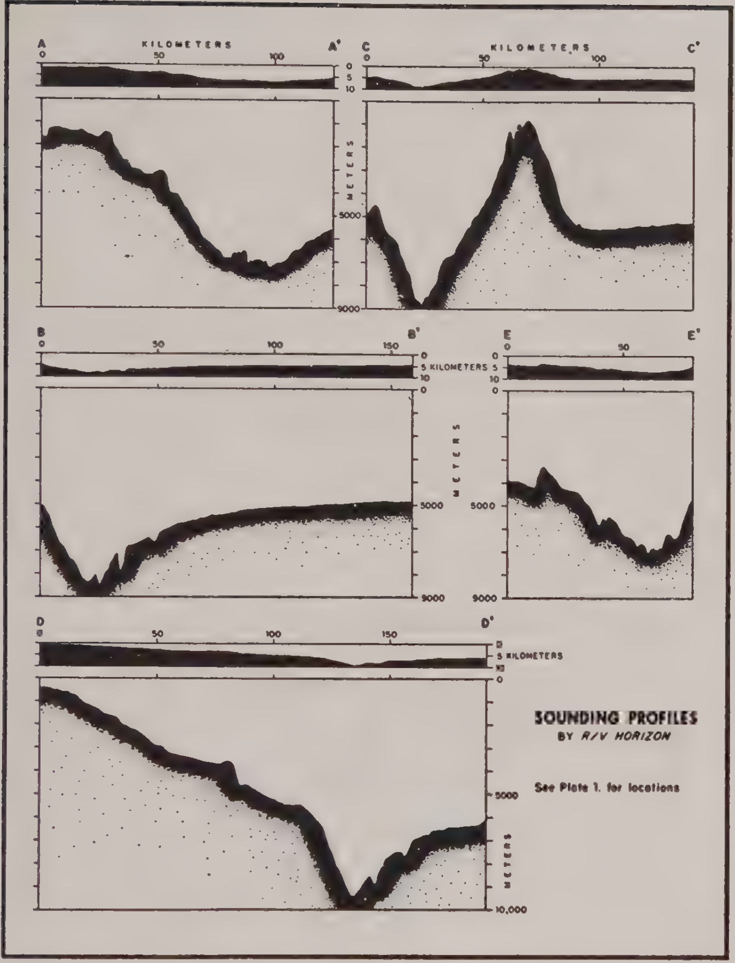

FIGURE 2.—*Continuous echo-sounding profiles across the Tonga Trench*

Plotted from HORIZON traverses. In each pair the upper, solid profile is plotted at natural scale; each partially shaded profile has a 10 × vertical exaggeration.

flat areas adjoining several of these peaks are assumed to be formed by damming of sediments carried down the trench walls.

Two trench crossings between A-A′ and B-B′, not illustrated in Figure 2, show that the trench bottom there is about 4 km wide and very flat, again suggesting sedimentary fill.

Profiles B-B′ and D-D′ are typical of the cross sections recorded over the central, V-shaped portion of the trench. The shoreward wall is steep and fairly regular, while the offshore wall may have several steep peaks near the trench bottom. No evidence of sedimentary fill was observed on these profiles; however, echoes from narrow flat

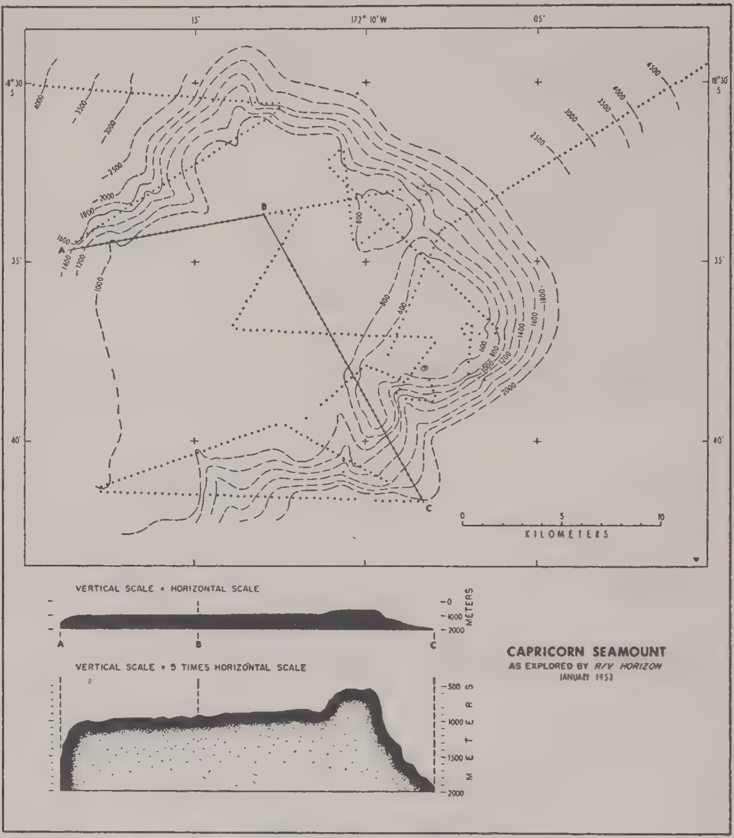
15'
172° 10'W
05'
18°30' S
35'
40'
A
B
C
0
5
10
KILOMETERS
VERTICAL SCALE = HORIZONTAL SCALE
0
1000
2000
METERS
VERTICAL SCALE = 5 TIMES HORIZONTAL SCALE
500
1000
1500
2000
METERS
CAPRICORN SEAMOUNT
AS EXPLORED BY *R/V HORIZON*
JANUARY 1953

FIGURE 3.—*Capricorn Seamount*

A westward-tilted seamount or guyot on the east flank of the Tonga Trench, about 180 km east of Vava'u.

trench floors could be masked by side echoes from the walls. Small elevations within the trench shown on such profiles are probably volcanic peaks, with basement rock exposed or veneered by sediments.

Profile C-C′ is very similar to B-B′ except in the central part, where a seamount constricts the trench on the east. Nearly flat on top (*see* Fig. 3), this peak rises smoothly more than 8500 m above the trench bottom and 5000 m above the general level of the sea floor eastward. No bordering depression suggestive of subsidence under the superimposed load of the seamount was found.

Figure 3 is a bathymetric plot of the upper portion of the seamount on the trench flank east of Vava'u. A single shoal sounding of 470 m, printed on several general bathymetric charts, lies about 20 km east of this seamount; it is almost certainly from the top of this peak. Though this peak is not an expedition find, the name Capricorn Seamount is proposed for it.

Most of the summit of Capricorn Seamount is a flat surface, sloping gently (45′-1°) to westward, so the term guyot may be applicable. The shoaler portions, separated from the deeper flat surface by a north-northeast trending scarp, lie on the southeast side of the peak. The flat surface was probably cut by wave action when sea level was much lower relative to the seamount. If so, the rather flat knoll, also sloping westward, may be either an erosional remnant of volcanic material or a drowned coral platform. The shoalest sounding, 395 m, is on the southeast edge of the upper level, part of a ridge running along the east side of the knoll. Three unsuccessful dredge hauls, just below the break in slope, were attempted; however, in each case the dredge caught firmly on hard bottom.

The age of Capricorn Seamount, relative to the age of the trench, is not known. Suggestion that the seamount is younger than the major trench-forming period is furnished by an examination of slopes of the sea floor and similarities in adjacent profiles B-B′ and C-C′. Neglecting the seamount, the profiles are similar as to slopes and depths at corresponding distances from the trench axis. The seamount's flat top slopes westward at 45′–1°; the bottom slopes on profile B-B′ at corresponding distances from the axis are 3°–4° westward. If trench formation is dominantly a continuing process of down-bowing, the lesser tilt of the seamount surface suggests relatively late formation, or at least truncation. However, it is entirely possible that the tilt of the seamount surface is due purely to local adjustments and bears no relation to broader trench-forming processes. It could not be determined how much drowning is due to subsidence and how much to absolute rise in sea level.

The positions of bottom samples taken on the Capricorn Expedition are indicated on Plate 1. Samples taken with dredge, short gravity corer, or piston corer confirmed the bottom-sediment distribution described in the section on Bottom Sampling. The principal noncalcareous sediment is volcanic sand or gravel. The most significant results came from a lowering to 9800 m, at 20°30′ S. Lat., near the trench axis, when kinks in the wire prevented immediate raising of the coring tube. The corer was retrieved after dragging over the bottom for 4 hours; the tube had been lost, and the lead weights deeply scarred and pitted. Fragments of volcanic rock were found embedded in the weights, showing that such rocks outcrop in the deep portion of the trench.

SEISMIC-REFRACTION STUDIES

Seismic-refraction studies were made with R/V Spencer F. Baird as receiving vessel and R/V Horizon as source vessel. Sources were TNT bombs made up from demolition charges, in sizes between half a pound and 80 pounds. They were dropped while Horizon was underway, usually at 11 knots, and fired at a depth usually between 100 and 200 feet with slow burning fuse cut to the appropriate length.

Sound waves from the shots were received at Spencer F. Baird on three hydrophones suspended from surface buoys at a depth of 200 feet. They were recorded photographically with a multi-channel oscillograph, which permitted selective filtering to enhance the seismic-refracted waves and to separate the water-borne sound used to survey the shot distances. Timing accuracy was fork-controlled and was frequently calibrated by comparison with radio time signals from WWV.

Shot distances were determined from the travel times of the direct sound waves from shot to receiver. Sound velocity for this purpose was determined by the measured water temperature and salinity, using Kuwahara's (1939) tables. During the Tonga observations this velocity was 1538 m/sec.

The lines of shots and the receiving stations are indicated in Plate 1. All the lines are roughly parallel to the trend of the structure in order to reduce the difficulties of interpreting seismic-refraction data when velocities and structure vary along the profile as well as with depth.

The western line runs through the long narrow Tofua Trough which lies between the chain of active volcanic islands and the main Tongan chain of coralline islands. This region was the nearest area to the trench on the west side that was suitable for refraction profiles of the length desired for crustal studies. It would have been desirable to have a similar line running along the main Tonga Ridge, but the dangers of navigating among the numerous uncharted shoals in this region made it inadvisable.

The greatest effort was expended on the lines along the axis of the trench where four profiles were recorded at two receiving stations opposite the central Tongan Islands. This work also proved to be most difficult, partly because of weak refracted arrivals and partly because of interpretation difficulties introduced by the great depth and bottom relief.

On the east flank the lines of shots were placed along the depth contour well up on the side of the trench where the depth is approximately equal to the average depth of the deep Pacific to the east.

TRAVEL-TIME DATA

The travel times of the first arrivals of bottom-refracted waves are plotted for the three lines of shots in Figures 4, 5, and 6. There were usually numerous secondary

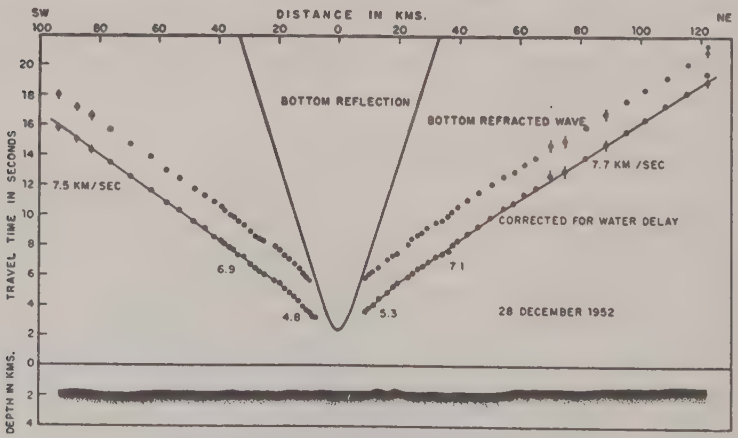

FIGURE 4.—*Travel-time data for Tofua Trough profiles*

Upper set of points represents uncorrected travel time. Lower set has been corrected for time delay in the water layer.

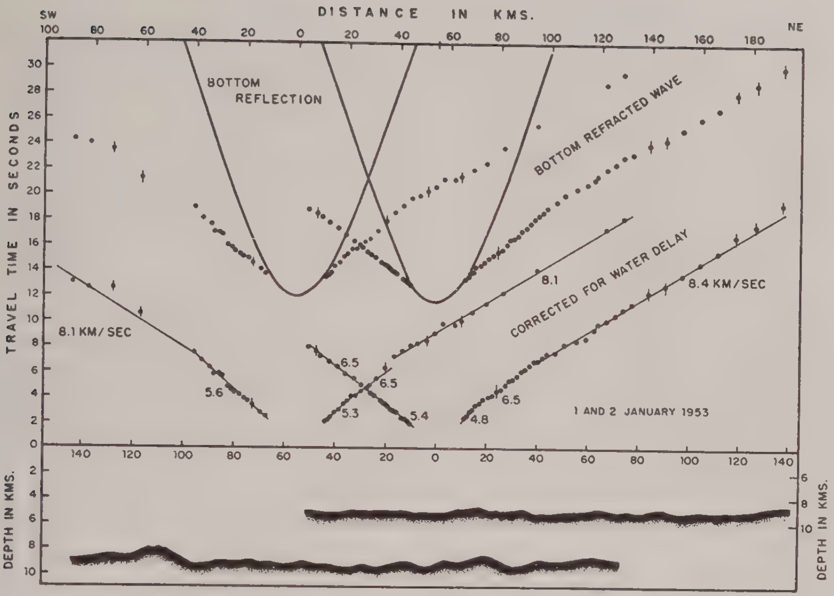

FIGURE 5.—*Travel-time data for Tonga Trench profiles*

Note that the depth scale of the bottom profile has been shifted for the right-hand receiving station, in order to separate the overlapping profiles.

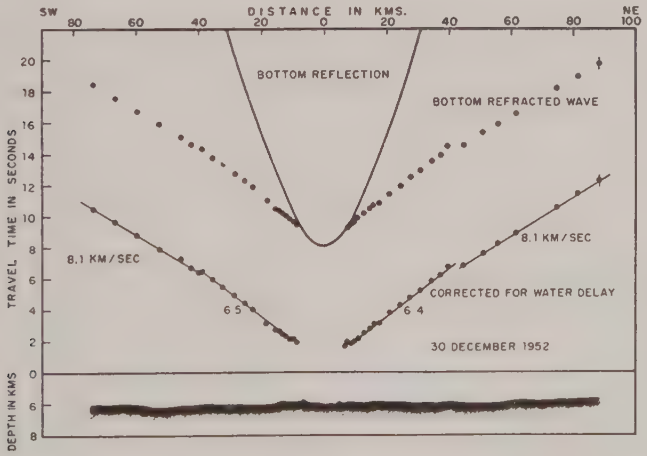

FIGURE 6.—*Travel-time data for profiles along the east flank of the Tonga Trench*

arrivals recorded after the first refracted waves, but only rarely did they form a simple enough pattern on successive shots to be used for a reliable determination of structure. Consequently only the first arrivals were used in the present interpretation. For ocean depths as great as those found in the Tonga Trench, a large part of the travel time of the bottom-refracted waves is used to travel from the sea's surface to

TABLE 1.—*Velocities and thicknesses of refracting layers*

Section	First Layer		Second Layer		Third Layer		Fourth Layer	
	Velocity, km/sec	Thickness, km	Velocity, km/sec	Thickness, km	Velocity, km/sec	Thickness, km	Velocity, km/sec	Thickness, km
Tofua Trough	2.0*	1.9	5.1	3.0	7.0	5.2	7.6	.....
Tonga Trench	.....	<0.2	5.3	3.0	6.5	8.2	8.2	.....
East Flank	2.5*	0.4	5.1*	0.6	6.5	4.5	8.1	.....

* Assumed Velocity

the bottom and return. Hence, in order to compare travel-time data taken in areas of different sea depth, it is desirable to eliminate the effects caused by depth differences.

In the figures both the observed travel times and the travel times corrected for the water column are shown. The water-delay correction gives the travel time that would be observed if shot and receiver had been placed on the bottom directly under their actual positions.

The differences among the three areas are much greater for the uncorrected than for the corrected travel times. The correction also tends to make the individual points line up better and thus give more accurate velocity information. In the case of the observations along the trench axis (Fig. 5), uncertainty in the magnitude of the depth to be used to make this correction contributed to the larger scatter of the corrected points. Hence the velocity data are less precise in this region.

VELOCITIES AND THICKNESSES

In most cases the travel-time plots of Figures 4, 5, and 6 are formed of linear segments, the wave velocities of which are indicated in the figures in km/sec. Calculation of the velocity structure was based on the usual simplified model made up of layers of constant velocity corresponding to the average slopes of corresponding segments of the travel-time plots. No attempt was made to determine detailed structure variations along the profiles. The objective was to derive for each set of profiles a minimum number of layers of constant velocity and thickness giving the best average fit to the observed travel-time data.

The results of this interpretation are given in Table 1. Four layers were identified for each section with velocities increasing from 2 km/sec to 8.2 km/sec. Velocities of the first layer, which represents sediment, were not measured directly because the refracted waves through this layer were not observed as first arrivals. The value of 2.0 km/sec assumed for the Tofua Trough is reasonable for an unconsolidated sand and gravel from the near-by volcanoes. If the sediment velocity had been much more than 2 km/sec its great thickness would have caused its observance as a first arrival at short range.

On the east flank, conditions are very similar to the average deep-Pacific situation where the rate of deposition is much slower and the sediment can be expected to be partially consolidated. A velocity of 2.5 km/sec was assumed for this sediment. A value of 5.1 km/sec was assumed for the second layer on the east flank because at this station the few close-range points at which this wave was observed merely indicate its order of magnitude but did not give a precise measurement.

IDENTIFICATION OF THE LAYERS

FIRST LAYER

The first layer is sediment and has been discussed in previous sections. In the trench the initial travel-time segments of 5.3 km/sec average velocity had zero intercept, indicating negligible sediment on the average. Although the data have a fairly large scatter because of the rough topography, it is estimated that a thickness of 200 m would have been measurable. Hence it is concluded that the sediment thickness in the trench is less than 200 m. Because of the steep walls of the inner gorge and the difficulty of keeping ship's position precisely in the center of the trench, this sediment thickness represents an average for a zone extending up the sides of the trench to a height of 500 m to 1000 m above its deepest part. It is possible that a narrow strip of sediment in the center of the trench has a thickness greater than 200 m. If so, it would be very difficult to measure, yet it would not change significantly the conclusion that there is very little volume of sediment in the section of the trench covered by the seismic profiles.

SECOND LAYER

The second layer forms the basement beneath the sediment. There is no evidence that its velocity varies systematically from a value of 5.2 ± 0.1 km/sec. Although this velocity could be characteristic of either a hard sedimentary rock or a soft igneous rock the widespread presence of volcanic rock in the area is a strong indication that the basement is volcanic. Additional evidence for this identification is given by the measurement by Leon Knopoff (1954, private communication) of a compressional wave velocity of 5.07 ± .07 km/sec for a sample of lava collected from the island of Tafahi at the northern end of the Tonga chain.

THIRD LAYER

The velocity of 6.5 km/sec for the third layer beneath the Tonga Trench and the east flank of the trench is somewhat lower than the average value for the deep Pacific of about 6.8 km/sec.

The value of 7.0 km/sec found beneath Tofua Trough is somewhat higher. The difference between 6.5 and 7.0 km/sec is about the order of magnitude of range of variation observed for all the deep Pacific observations. Hence the seismic data do not prove that the crust in the trench or on either side is systematically different from the Pacific oceanic crust. If any significance is to be attached to the difference it would be that the crustal velocity beneath the Tonga Archipelago is higher and hence less continental than that beneath the trench and the Pacific basin to the east.

FOURTH LAYER

The values of 8.2 and 8.1 km/sec attained in the trench and on the east flank, respectively, represent mantle velocities below the Mohorovičić discontinuity in the usual meaning of the term. The velocity of 7.6 km/sec, reached at an estimated depth

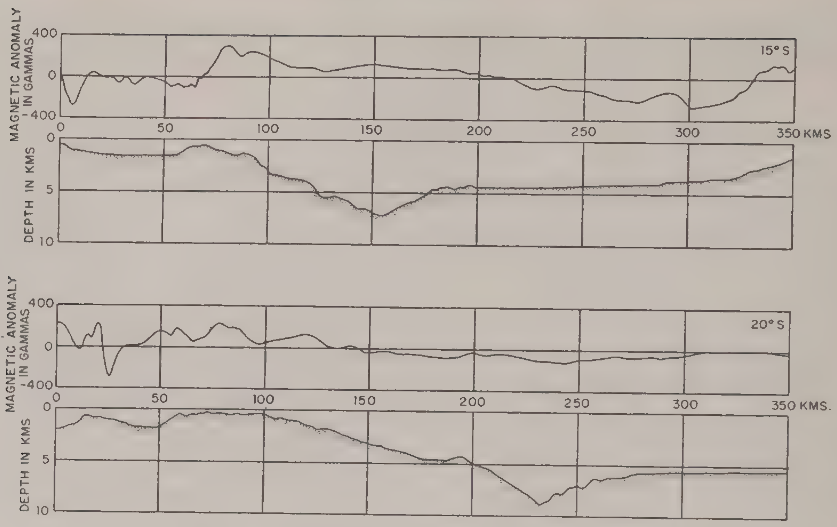

FIGURE 7.—*Magnetic profiles across the Tonga Trench*

of 11.8 km below sea level under the Tofua Trough, is significantly less. Failure to observe mantle velocity at Tofua Trough may have been because it is (1) too deep to be detected as a first arrival at the maximum shot distance; or (2) its refracted wave is present as a first arrival but too weak to be detected. If (1) is correct then the Mohorovičić discontinuity must be at least 18 km below sea level beneath Tofua Trough.

MAGNETIC STUDIES

A continuous record of total magnetic field was obtained over about 100 km of track in the Tonga area (Pl. 1), using a type AN/ASQ3A air-borne magnetometer modified for geophysical use and subsequently adapted by the Lamont Geological Observatory for towing in the water behind a ship (Heezen, Ewing, and Miller, 1953).

From this data two profiles were obtained normal to the axis of the trench, each about 350 km long. The more northerly, at about 15° S., runs in a continuous straight line from Tafahi on the west to Tutuila on the east, crossing the trench at its northern end where it bends to the northwest. The other, at about 20° S., running east from the neighborhood of Kao, was assembled from several segments approximately in line with one another and passing through seismic stations in the Tofua Trough, over the axis of the trench, and 50 km east of the trench.

The northern line is nowhere more than 250 km from the magnetic observatory at Apia, Western Samoa, and so corrections can be applied for diurnal variation, but the other is too far away to permit reliable corrections. However, most of the data on this line were obtained at night when variations are usually small.

The magnetic anomalies remaining after removal of the earth's normal field are shown in Figure 7, together with the corresponding bathymetric profiles. To avoid the removal of any magnetic features of significance the gradient has been assumed

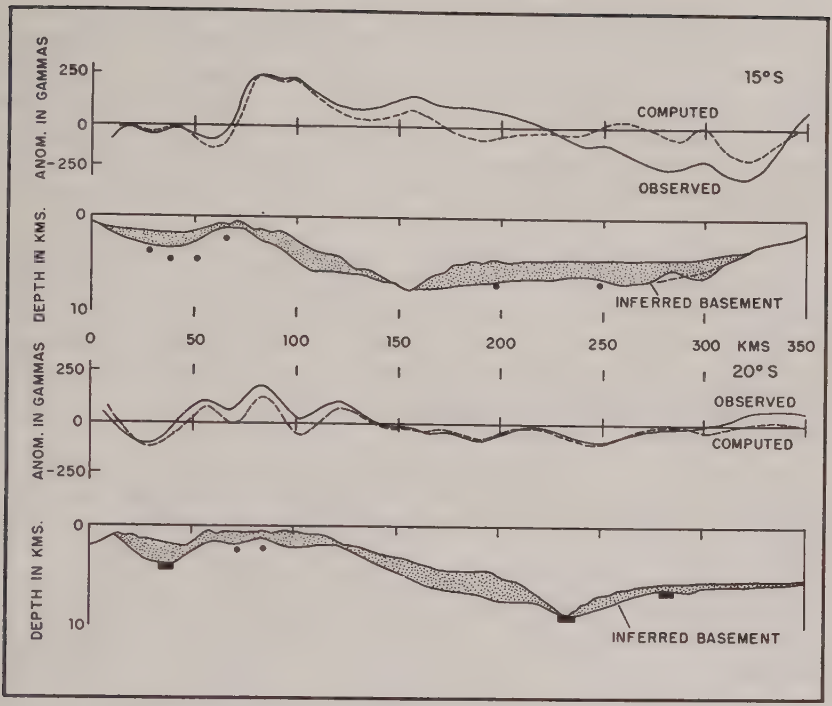

FIGURE 8.—*Basement structure inferred from magnetic profiles*

uniform over the length of each line. Both profiles show maximum deviations of about ±250 gammas in the shoal areas; over the deeper parts of the trench departures from a straight line are less than ±10 gammas in 10 km.

If the effect of permanent magnetization is ignored and the trench treated as a uniform two-dimensional structure then it is possible to construct basement sections to fit the observed anomalies, given the depth at one or more points and a value for magnetic susceptibility. Figure 8 shows the observed anomalies smoothed over intervals of 5 km for ease of handling, the computed anomalies judged to provide the best fit, and the inferred basement sections.

In the absence of seismic data the basement rock in the northern section is assumed to crop out at the ends of the line and at its deepest point in the bottom of the trench. The southern section has been fitted to the depths indicated by the seismic observations and shown by solid bars. On both lines some depths, indicated by large dots, have been estimated from the "half-width" of suitable anomalies, a method which generally overestimates depth. A value of 0.01 c.g.s. units was selected for susceptibility based on the anomalies associated with the Kao and with other small-scale features. Other workers have used values ranging from 0.005 to 0.01 c.g.s. units (Alldredge and Dichtel, 1949; Keller, Meuschke, and Alldredge, 1954).

In general the magnetic data suggest greater thickness of sediment than anticipated, particularly on the lower parts of the eastern slope in the southern section where the seismic evidence points to less than 200 m of sediment. This apparent discrepancy may be explained by the different nature of the response of echo sounder and magnetometer to the volcanic peaks believed to occur on this slope, and in other places. The echo sounder traces the upper surfaces of these peaks and underestimates the depth; individual peaks, even of 1 km elevation, are too small and too deep to produce measurable anomalies at the surface, and so the magnetometer indicates a mean depth.

Thicknesses of up to 2 km of sediment are indicated on the northern section extending from the axis of the trench 150 km to the east. This thickness is unusual in the Pacific but may be related to the change in direction of the trench. The fit of the two curves can be improved by moving the deepest part of the basement 10 km to the east leading to a greater thickness of sediment near the axis of the trench and rather less east of the 200-km point. The anomaly at 300 km may be due to an unsuspected seamount 5 to 10 km to the south.

Comparison of observed and computed curves shows an excess of magnetism on the west side of the trench and a deficiency on the east not easily accounted for by any reasonable configuration of the basement. This could arise from one or more sources:

(1) A larger value of susceptibility on the west side. The susceptibility would have to decrease gradually by about 50 per cent from the western end of the profiles to the axis of the trench. It is perhaps significant that seismic velocities are higher on the west side.

(2) Changes in the levels of the various interfaces indicated by the seismic studies. If basicity and susceptibility increase with depth there would have to be an upwarping of the layers under the islands and a downwarping east of the trench. This appears contrary to the seismic indications.

(3) A downwarping of the Curie isothermal surface, beneath which the rock is presumed nonmagnetic, under the islands and an upwarping to the east. Assuming a mean depth of 25 km a downwarping of about 5 km would be necessary under the islands with a similar rise to the east. This is consistent with the seismic picture.

STRUCTURE

In Figure 9 an attempt has been made to summarize the results of the topographic, seismic, and magnetic studies of the central part of the Tonga Trench. It represents a schematic cross section, normal to the axis of the trench, passing through the island Kao, grazing the southern edge of Lifuka, and passing up the east flank to about 90 km east of the trench axis. The trench portion of the cross section has been generalized to represent an average section in that region. Consequently many of the details which would be present in an actual section are missing.

At the positions where the seismic lines cross the section the depths of the various layers tabulated in Table 1 are indicated by hatched interfaces. The three dashed lines delineating the crustal layers are very rough estimates of possible interpolations. The upper one, which represents the interface between the sediment and the igneous basement, has been estimated from the southerly magnetic profile. The other two dashed interfaces are hypothetical except at the positions of seismic control.

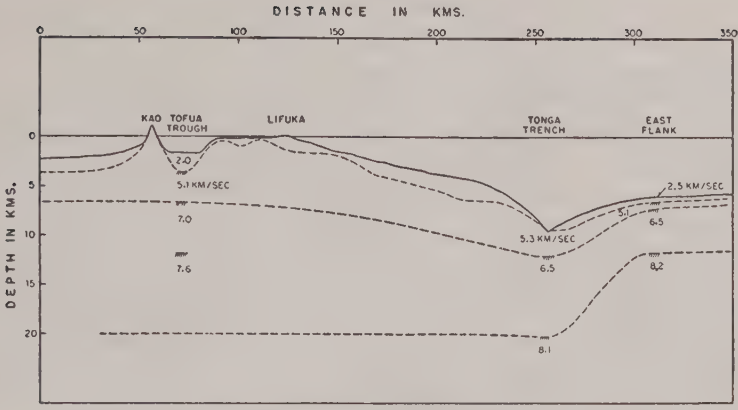

FIGURE 9.—*Structure section deduced from seismic and magnetic data*

Although the sparse distribution of the subsurface information presents an incomplete description of the illustrated section, several conclusions can be made regarding general features:

(1) The Mohorovičić discontinuity is 20 km below sea level under the trench. This is 8 km deeper than its depth in the Pacific basin to the east. The change in depth takes place in a distance of 50 km or less.

(2) West of the trench, the depth of the Mohorovičić discontinuity is restricted only by the estimate that it is at least 18 km below sea level under Tofua Trough.

(3) The velocity of the crust is 6.5 km/sec beneath the trench and the east flank. It is 7.0 to 7.6 km/sec beneath the Tonga ridge. There is no evidence for a substantial thickness of continental sialic material with a velocity of the order of 6 km/sec.

(4) A layer of velocity 5.2 ± 0.1 km/sec forms the basement beneath the sediment. It is probably volcanic. Its thickness is of the order of 5 km beneath the Tongan ridge, 3 km beneath the trench, and decreases to about 0.6 km on the east flank. It crops out in the volcanic islands and in the bottom of the trench. It has considerable surface relief and rises close to the surface in buried peaks under the coralline deposits of the main Tonga ridge.

Comparison of this structure with that deduced from seismic and gravity measurements in the Puerto Rico Trench by Ewing and Worzel (1954) shows that the most striking difference is the quantity of sediment, which is very abundant in the Puerto Rico Trench and nearly absent in the deepest part of the Tonga Trench. A less striking difference is the higher basement velocity of 5.5 to 6 km/sec under Puerto Rico compared to the 5.2 km/sec observed at Tonga.

Both these differences suggest that Tonga Trench is younger than Puerto Rico Trench. For, as the volcanic eruption continues to build up the Tonga ridge, it will not only supply sediment to the trench but will also increase the basement velocity by the added weight of the erupted material. If during this process the forces producing the trench continue to widen and deepen it, then it is reasonable to expect Tonga to become more like Puerto Rico.

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SOME PROBLEMS IN OPTICAL OCEANOGRAPHY[1]

BY

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ABSTRACT

Problems involving the refraction and reflection of light from sun and sky by a *roughened* sea surface have been made accessible to numerical treatment by measurements of the probability distribution of sea surface slopes. Four cases are treated. (1) The refracted sun's glitter, as seen from beneath the surface. It is smaller but about 1000 times more luminous (neglecting absorption) than the reflected glitter, and, unlike the reflected glitter, it expands and dims as the sun sets. (2) The albedo of a rough surface to direct sunlight. It is slightly larger at high sun angles and substantially smaller at low sun angles than the albedo of a flat surface. Accordingly, more solar energy penetrates arctic waters than had been estimated previously and the amount of this additional energy depends upon wind speed. (3) The luminosity and albedo of a rough sea surface due to sky light. At the horizon a rough surface is darker than a smooth surface, thus enhancing the horizon contrast. The albedo of the sea surface to sky light varies from 5 to 10%, depending on the distribution of illumination from the sky; it is largest when the sea is flat calm. The roughening by a Beaufort 4 wind reduces the albedo by about 20%. (4) The visibility of slicks.

1. INTRODUCTION

Measurements of the probability distribution of slopes have been made by Duntley (1950), Schooley (1954), and by Cox and Munk (1954a and b). As a result of these measurements, certain oceanographic problems have become accessible to numerical treatment. In these problems we are concerned with the *average* brightness ("radiance" in optical terminology) of the sea surface due to sun or sky when viewed from above or beneath. The average is formed over sufficient time or sufficient surface area to smooth out fluctuations such as the ones that result from individual glitter sparkles of sunlight. The average is then essentially independent of time but varies smoothly with the azimuth and elevation of the portion of sea surface under consideration.

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[1] Contribution from the Scripps Institution of Oceanography, New Series No. 776. This work has been sponsored in part by the Geophysics Research Directorate of the Air Force Cambridge Research Center, Air Research and Development Command, under Contract No. AF(19) 604 (1053).

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Let $z(x, y)$ designate the elevation of the sea surface above a mean level and let $\partial z/\partial x = z_x$, $\partial z/\partial y = z_y$ be the corresponding slope components. We shall require the probability $p(z_x, z_y)\delta z_x \delta z_y$ that the slope components will lie within the limits $z_x \pm \frac{1}{2}\delta z_x$, $z_y \pm \frac{1}{2}\delta z_y$. As a first approximation, we find (Cox and Munk, 1954a: section 6.3) that the distribution is Gaussian,

$$p(z_x, z_y) = (\pi\sigma^2)^{-1} \exp\left[-(z_x^2 + z_y^2)/\sigma^2\right] . \qquad (1)$$

The mean square slope, regardless of direction, $\sigma^2 = < z_x^2 + z_y^2 >_{AV}$, increases with the "masthead" wind speed in $m\ s^{-1}$, W, according to

$$\sigma^2 = .003 + 5.12 \times 10^{-3} W \pm .004 . \qquad (2)$$

In the presence of a slick this value is reduced by a factor of two or three.

In adopting the isotropic Gaussian distribution function (1) we simplify our results at the cost of omitting certain observed effects of wind directionality. For it has been found (Cox and Munk, 1954a: sections 6.3, 6.4) that the up/downwind slope components exceed the crosswind components and that the up/downwind distribution is skewed.

2. THE GLITTER AS SEEN FROM BENEATH THE SURFACE

The same glitter pattern differs substantially when viewed from above and below the sea surface. These differences are illustrated in Fig. 1 and are described in the legend. The upper part of Fig. 1 is based on the theory of *reflected* glitter as given previously (Cox and Munk, 1954a: sections 3.1, 3.2). The theory for *refracted* glitter (lower part of Fig. 1) is developed along similar lines in the following sections.

The principal differences between the reflected and refracted glitter patterns are as follows: (1) The reflected glitter pattern is larger[2] and less luminous than the refracted pattern. (2) The reflected pattern shrinks and becomes more luminous as the sun sets; the reverse holds for the refracted pattern. (3) Both reflected and refracted patterns move toward the horizon with the setting sun, but the reflected pattern moves almost twice as fast.

In a general way these conclusions are in agreement with what has been observed. However, at ordinary diving depths the luminescence varies considerably with the passage of individual waves, whereas the patterns described here correspond to suitable time exposures. The fluctuations diminish with increasing depth, so that at a depth of, say

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[2] The refracted patterns in Fig. 1 are enlarged by a factor of 2.5 relative to the reflected patterns.

(382)

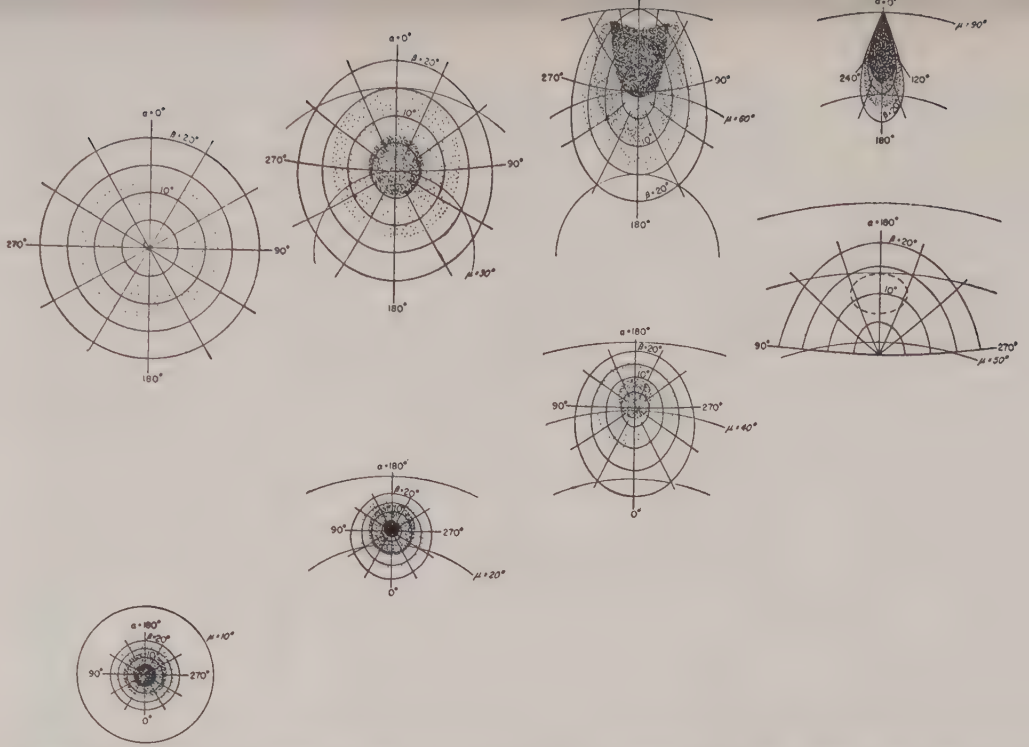

Figure 1. The glitter patterns for a Beaufort 4 wind ($W = 7\ ms^{-1}$, $\sigma = 0.2$) as seen from above the surface (Upper Four) and from beneath (Lower Four). The patterns from left to right are drawn for solar zenith angles of 0° (sun at zenith), 30°, 60°, 90° (sun at horizon). Each pattern is drawn with reference to the polar coordinates μ, the observer's zenith angle, and ν, the azimuth relative to the sun (see Fig. 2). The value $\mu = 0°$ designates a point on the surface directly beneath (above) the observer; the horizon is at $\mu = 90°$. The circular arcs in the upper patterns are drawn for $\mu = 30°, 60°, 90°$, in the lower patterns for 10°, 20°, . . . 60°, 70°. The μ-scale in the lower figure is 2.5 times the scale in the upper figures. For each diagram the radial α-lines give the azimuth of ascent, and the quasi-elliptical β-lines the tilt required for the occurrence of a highlight (Fig. 2). Shadings indicate surface luminosity. The values in units of the sun's luminosity are as follows:

shading	*none*	*light*	*medium*	*heavy*
upper figures: (parts per million)	$<.66$	.66–3.3	3.3–16.6	>16.6
lower figures: (parts per thousand)	$<.25$	.25–1.3	1.3– 6.6	>6.6

1000 feet, the observed pattern would resemble the computed pattern rather closely were it not for the effect of absorption (which we have ignored) and other difficulties.

Whitecaps have been neglected. At low sun angles the effects of multiple scattering and wave shadowing introduce a serious error into our calculation, and the angular dimension of the sun as compared to the reflected pattern should also be taken into account. All constants have been computed for an isotropic slope distribution. Under actual conditions, the most probable slope is a few degrees, not zero, and its azimuth of ascent is directed downwind. The result is an upwind displacement of the bright core of the glitter.

2.1. *The geometry of refraction.* The following derivation follows closely the derivation of the geometry of reflection attained previously (Cox and Munk, 1954a: section 3). We can therefore give an abbreviated account. All angles are defined in Fig. 2. The azimuth of ascent, α, and the tilt, β, are related to the slope components z_x, z_y according to

$$z_x = \sin\alpha \tan\beta, \quad z_y = \cos\alpha \tan\beta \,. \tag{3}$$

According to the law of refraction, a unit vector along the incident ray *minus* a vector of length n along the refracted ray[3] equals a vector normal to the refracting surface. This vector equation has the components

$$\begin{aligned} -\sin\psi - n\sin\mu\cos\nu &= -k\cos\alpha\sin\beta \\ -n\sin\mu\sin\nu &= -k\sin\alpha\cos\beta \\ -\cos\psi + n\cos\mu &= k\cos\beta \,. \end{aligned} \tag{4}$$

The factor k may be found by eliminating μ and ν. This yields

$$k = n\cos\omega_r - \cos\omega \tag{5}$$

where

$$\cos\omega = \cos\beta\cos\psi - \cos\alpha\sin\beta\sin\psi, \quad n^{-1}\sin\omega_r\sin\omega \,.$$

It can be verified that ω and ω_r are the angles of incidence and refraction with the surface normal. Solving equations (4) for μ and ν, we find the "grid" relations:

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[3] The index of refraction, n, depends on the frequency of light. In the subsequent calculations we have assumed a value $n = 1.34$ corresponding to yellow light. This value is an appropriate average for phenomena depending on the total energy of sunlight.

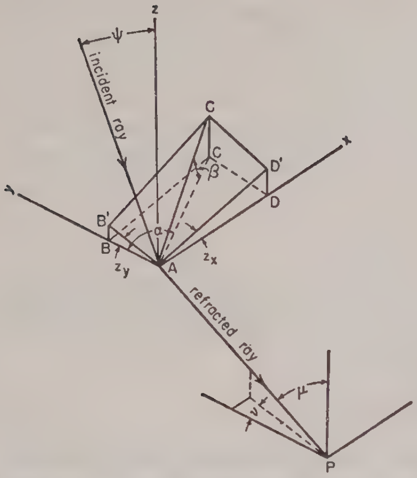

Figure 2. The coordinate system is centered at the sea surface with the z-axis vertically upward and the y-axis horizontal and toward the sun. The incident ray is refracted at A toward the observer at P, where it forms an angle μ with the vertical, and an azimuth ν to the right of the sun. Points ABCD define a horizontal plane through A, and $AB'C'D'$ a plane tangent to the sea surface. The tilt, β, is measured in the direction, AC, of steepest ascent, and this direction makes an angle α to the right of the sun.

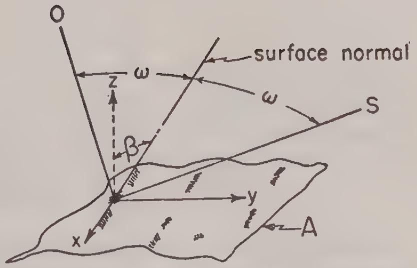

Figure 3. "A" is a unit of sea surface. The shaded portions indicate all points where the slopes lie within designated limits $z_x \pm \frac{1}{2}\delta z_x$, $z_y \pm \frac{1}{2}\delta z_y$. The average tilt in the shaded areas is β, where $\tan^2\beta = z_x^2 + z_y^2$. The y-axis is drawn away from the sun. Incident rays from the sun at O are reflected toward S. In the discussion of sky light (Sec. 4), the direction of rays is reversed. Incident rays from the sky at S are reflected toward the observer at O. In *both* cases the angle of the incident ray with the z-axis is designated by ψ and of the reflected ray by μ.

$$\begin{aligned} \cos\mu &= n^{-1}(\cos\psi + k\cos\beta) \\ \cot\nu &= \cot\alpha - (k\sin\alpha\sin\beta)^{-1}\sin\psi\,. \end{aligned} \tag{6}$$

Any point on the sea surface can be characterized by its zenith angle μ and direction ν. In the eight diagrams of Fig. 1, the angles μ, ν are represented by polar coordinates; μ is the radial distance and ν the angular coordinate. On these polar diagrams, curves of constant $\alpha(\mu, \nu)$ and $\beta(\mu, \nu)$ for various solar zenith angles ψ have been drawn according to the grid relations. An observer looking upward to a point μ, ν at the surface will see such facets highlighted that have the slope given by these curves.

2.2. *Surface radiance.* This section corresponds to the previously discussed case of reflection (Cox and Munk, 1954a: section 4). Individual highlights form distorted images of the sun. According to a general law of optics, the radiance (power per unit solid angle per unit area normal to the beam) radiated by an image in a medium of refractive index n is (n^2) times the radiance of the object (in open space) reduced by any transmission losses of the optical system. Accordingly, the radiance within a highlight is $B' = n^2 \tau B$, where τ is the transmission of the sea surface and B is the radiance of the surface of the sun. According to Fresnel's formula for unpolarized light, $\tau = 1 - \rho$, where

$$2\rho = \sin^2(\omega - \omega_r) \csc^2(\omega + \omega_r) + \tan^2(\omega - \omega_r) \cot^2(\omega + \omega_r) \,. \quad (7)$$

The *total* power radiated per unit solid angle by the entire highlight is therefore $I = B' \Delta_s$, where Δ_s is the area of the highlight projected normal to the line of sight. Designating the horizontally projected area of the highlight by Δ_h, this becomes

$$I = n^2 \tau B \Delta_h \sec \beta \cos \omega_r \,. \quad (8)$$

The highlighted areas of the sea surface are those for which the sea surface has the appropriate tilt and azimuth of ascent to satisfy equations (6) within a small "tolerance" which allows for the fact that rays may originate at any point on the sun's face. This imposes limits on the permitted variation of α, β, or alternatively z_x, z_y, within the highlight. It may be shown that the area on the z_x, z_y-plane corresponding to the permitted variation of slopes within a highlight is

$$\delta z_x \, \delta z_y = \varepsilon \, k^{-2} \cos \omega \sec^3 \beta \,, \quad (9)$$

where ε is the solid angle subtended by the sun.[4]

The fraction of the (horizontally projected) sea surface which has slope components within the required limits $z_x \pm \frac{1}{2}\delta z_x$, $z_y \pm \frac{1}{2}\delta z_y$, is $p(z_x, z_y)\delta z_x \delta z_y$, where p is the probability distribution of slopes (Eq. 1). Hence the average power radiated by all highlights within a horizontal unit area of sea surface is $p\delta z_x \delta z_y I$. The average radiance N of the sea surface in the line of sight (power per unit solid angle per unit area *normal* to the beam) is this value multiplied by $\sec \mu$. Substituting from (8) and (9), we obtain

$$N = n^2 \tau H k^{-2} p \sec^4 \beta \cos \omega_r \cos \omega \sec \mu \,. \quad (10)$$

Here we have replaced $B\varepsilon$ by H, the irradiance (power per unit area) received at the sea surface from the sun.

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[4] The solid angle subtended by a highlight is assumed small compared to the angle subtended by the sun. The highlighted areas are of the order of 0.1 mm^2, so that this assumption holds except within a few centimeters of the sea surface. In addition, the angular size of the sun is assumed to be small compared to the angular dimensions of the glitter pattern. This assumption fails for low sun angles and for very small slopes.

The simplest case is that for a point directly above the observer ($\mu = z_x = z_y = 0$) with the sun at the zenith ($\psi = 0°$). This gives

$$N_0 = \left(\frac{n}{n-1}\right)^2 \left[1 - \left(\frac{n-1}{n+1}\right)^2\right] Hp\,(0,0).$$

For a point directly *beneath* the observer, the reflected radiance under similar circumstances equals (Cox and Munk, 1954a)

$$N_0' = \frac{1}{4}\left(\frac{n-1}{n+1}\right)^2 Hp\,(0,0).$$

The ratio of refracted to reflected radiance is

$$\frac{N_0}{N_0'} = 4\left(\frac{n}{n-1}\right)^2 \left[\left(\frac{n+1}{n-1}\right)^2 - 1\right] \doteq 3000.$$

The radiance from a perfectly diffusing surface (one that scatters uniformly into a solid angle 2π) is H/π.

3. REFLECTION OF DIRECT SUNLIGHT FROM A ROUGH SEA SURFACE

The reflection of direct sunlight is an important factor in the energy budget of the ocean. Estimates based on reflection from a flat water surface are in error because the average coefficient of reflection for a rough surface differs from that for a flat surface. The difference becomes appreciable for low solar elevations.

First we consider the reflection by facets whose slopes lie within the limits $z_x \pm \frac{1}{2}\delta z_x$, $z_y \pm \frac{1}{2}\delta z_y$. Their (horizontally projected) area within a unit area A (Fig. 3) is, on the average, $p(z_x, z_y)\delta z_x \delta z_x$. The actual (tilted) area is $\sec \beta p \delta z_x \delta z_y$. The projected area normal to the incoming rays from the sun is $\cos \omega \sec \beta\ p\delta z_x \delta z_y$. The radiant flux intercepted is $H \cos \omega \sec \beta\ p \delta z_x \delta z_y$. The reflected flux is

$$H\rho(\omega) \cos \omega \sec \beta\ p\delta z_x \delta z_y\,, \tag{11}$$

where $\rho(\omega)$ is given by Fresnel's formula (7). It is assumed that the incident light is not polarized and is reflected only once.

Equation (11) gives the reflected flux associated with slopes within the limit $z_x \pm \frac{1}{2}\delta z_x$, $z_y \pm \frac{1}{2}\delta z_y$. The total reflected flux per unit area of sea surface is then

$$H \iint \rho(\omega) \cos \omega \sec \beta\ p\,dz_x dz_y\,, \tag{12}$$

with the integration extending over all slopes exposed to the sun.

The radiant flux incident upon the unit area is $H \cos \psi$, where ψ is the sun's zenith angle. Consequently the fraction reflected, i. e. the *albedo*, is

$$R = \sec \psi \iint \rho(\omega) \cos \omega \sec \beta \, p dz_x dz_y \, . \tag{13}$$

For the special case of a level surface, $z_x = z_y = \beta = 0, \omega = \psi, \rho(z_x, z_y) = 0$ except at $z_x = 0$, $z_y = 0$. It follows that $R = \rho(\psi)$. For the general case, we make use of the law of reflection (Fig. 3)

$$\cos \omega = \cos \beta (\cos \psi + z_y \sin \psi) \, . \tag{14}$$

The quantities $F(\omega) = \rho(\omega) \cos \omega$ and $\sec \beta = (1 + z_x^2 + z_y^2)^{\frac{1}{2}}$ may now be expanded in Taylor's series in z_x, z_y around the values $z_x = z_y = 0$ for which $\beta = 0$, $\omega = \psi$. This yields

$$\mathrm{R} = \rho(\psi) \iint (1 + a z_y + b z_y^2 + c z_x^2 + \ldots) \, p dz_x dz_y \, , \tag{15}$$

where

$$a = -F'/F, \quad b = \tfrac{1}{2} + \tfrac{1}{2} F''/F, \quad c = \tfrac{1}{2} + \tfrac{1}{2}(F'/F) \cot \psi \, . \tag{16}$$

The functions F, $F' = dF/d\omega$, $F'' = d^2F/d\omega^2$ are evaluated at $\omega = \psi$.

If all slopes are less in magnitude than $90° - \psi$, then the sea surface is everywhere exposed to the sun and the limits are $\pm \infty$. In this case

$$R = \rho(\psi) \, (1 + b < z_y^2 >_{AV} + c < z_x^2 >_{AV}) \, . \tag{17}$$

Here we have made use of

$$< z_y >_{AV} = \iint_{-\infty}^{\infty} z_y p dz_x dz_y = 0$$

because the mean sea level is horizontal. To the present approximation the albedo depends only on the components of mean square slope along the sun's azimuth and normal to it; it does not depend on the form of $p(z_x, z_y)$. For the isotropic case, $< z_x^2 >_{AV} = < z_y^2 >_{AV} = \tfrac{1}{2} \sigma^2$, and

$$R = \rho(\psi) \, [1 + f(\psi) \, \sigma^2] \, , \tag{17a}$$

where

$$f(\psi) = \tfrac{1}{2}(b + c) = \tfrac{1}{2} + \tfrac{1}{4}(F'/F) \cot \psi + \tfrac{1}{4} F''/F \tag{17b}$$

is the "roughness" function plotted in Fig. 4. Some difficulties arise when ψ is large, and these will now be considered.

Large negative slopes in the component z_y are shadowed if they exceed $\cot \psi$. We shall allow for this "first order" hiding by setting the limits $(-\cot \psi)$ to ∞ for z_y (but $\pm \infty$ for z_x). This is equivalent to the limits 0 to 90° in the angle of incidence, ω. Because some additional slopes are hidden, the computed value of R will be too large for large ψ, but the evaluation of the "second order" hiding involves infor-

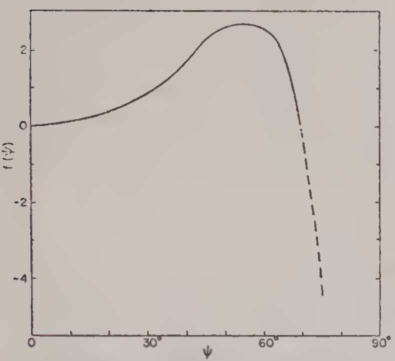

Figure 4. The roughness function $f(\psi)$ as defined in equation (17b). In the dashed portion near the horizon the function is not strictly applicable because of shadowing and multiple reflection.

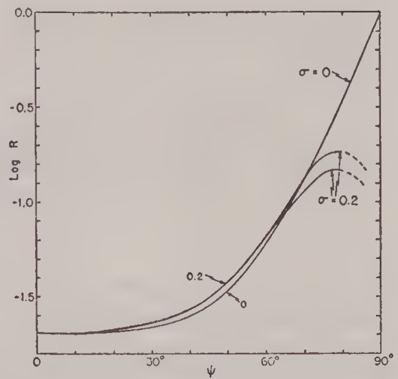

Figure 5. Reflection of solar radiation from a flat surface ($\sigma = 0°$) and a surface roughened by a Beaufort 4 wind ($\sigma = 0.2$). The albedo R varies from .02 for a zenith sun ($\psi = 0°$) to unity for the sun at the horizon ($\psi = 90°$) with the surface flat. For a rough surface, shadowing and multiple reflections become important factors when the sun is low. The lower and upper branches of the curve marked $\sigma = 0.2$ represent two assumptions regarding the effects of multiple reflection. True values are expected to lie between the indicated limits.

mation on the spectrum of ocean waves, and in the absence of such information we must restrict ourselves to the first order hiding.

The integration now yields

$$R = \rho(\psi)\ \{\tfrac{1}{2}[1 + I(k)] + \tfrac{1}{2}\pi^{-\frac{1}{2}}a\sigma e^{-k^2} + \\ + \tfrac{1}{4}\, b\sigma^2[1 + I(k) - 2\pi^{-\frac{1}{2}}\, ke^{-k^2}] + \tfrac{1}{4}\, c\sigma^2[1 + I(k)] + \ldots\} \quad (18)$$

where

$$k = \sigma^{-1} \cot \psi \quad (19)$$

and where $I(k) = 2\pi^{-\frac{1}{2}} \int_0^k e^{-t^2}dt$ is the error integral. The present approximation is adequate for large values of the dimensionless parameter k. For *very* large values, equation (18) converges on (17).

So far we have neglected multiple reflections. If the reflected ray goes toward a point *beneath* the horizon, then certainly there must be at least one further reflection. This "first order" multiple reflection requires that z_y be negative and exceed $\tfrac{1}{2} \cot \psi(1 - \tan^2 \beta)$ in magnitude. The product of coefficients of reflection of all but the first reflection is unknown but must lie between unity and zero. In the first extreme, multiple reflections would not alter R, and equation (18) is correct as it stands. In the latter extreme case, the integration with respect to z_y in equation (15) is between the limits $-\frac{1}{2}\cot\psi(1 - \tan^2\beta)$ and $+\infty$. These can be replaced by the limits $-\frac{1}{2}\cot\psi$ and $+\infty$ because of the heavy discrimination of the exponential factor in $p(z_x z_y)$ against contributions from large β. The limits on z_x remain $\pm\infty$. The result of this integration is again equation (18) but with k now designated by

$$k = \tfrac{1}{2}\sigma^{-1}\cot\psi \tag{20}$$

rather than by the quantity in equation (19).

Fig. 5 shows the average reflectivity of the sea surface bracketed by these two expressions as compared with the reflectivity of a flat surface. At high sun elevation, the albedo of the rough surface is slightly larger; for $\psi = 40°$ the values are 2.5% for the smooth surface and 2.7% for the rough surface. At low sun elevation, increasing roughness leads to a marked decrease in albedo. The only conclusion of oceanographic consequence seems to be that in summer substantially more energy must penetrate the open stretches of the Arctic Ocean than had been estimated previously and that the amount of this additional energy depends on the wind speed.

4. REFLECTION OF SKY LIGHT FROM A ROUGH SURFACE

The radiance of the sky is due to scattering of sunlight and reflected "earth light" by air molecules (Rayleigh scattering), dust, haze, clouds, etc. This varies in a complicated and rather unpredictable way over the sky dome. We shall consider the three cases illustrated in Fig. 6:

(a) a clear tropical sky at Bocaiuva, Brazil, from measurements[5] by Richardson and Hulbert (1949);

(b) a uniform sky dome;

(c) a completely overcast sky, whose radiance can be approximated by the empirical formula (Moon and Spencer, 1942)

$$N_s(\psi) = \tfrac{1}{3} N_s(0)(1 + 2\cos\psi)\,. \tag{21}$$

To simplify subsequent calculations we shall make all quantities depend only on the zenith angle ψ. This already holds for (*b*) and (*c*), but for (*a*) the sky depends largely on zenith angle. Accordingly we have ignored the increased radiance near the sun and have based our calculations on the observed radiance along an azimuth 90° from the azimuth of the sun. In the following calculations we also assume

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[5] The observations were made at 2200 feet; the sky radiance at sea level would be slightly different.

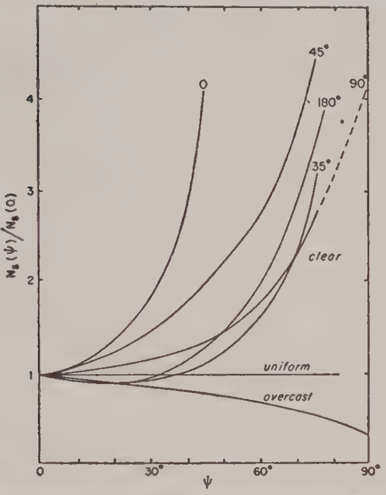

Figure 6. The radiance of the sky $N_s(\psi)$ divided by the radiance at the zenith $N_s(0°)$ as function of the zenith angle ψ. The curves for the clear sky are based on observation at Bocaiuva, Brazil, for the sun at $\psi = 60°$. They are drawn for indicated azimuths relative to the sun. Computations are based on the heavy curve marked 90°. The radiance for the overcast sky, based on the empirical law (21), applies to all azimuths.

unpolarized sky light.[6] Actually there is considerable polarization for a clear sky, and the polarization is a function of the azimuth relative to the sun.

The derivation is similar to that in the preceding section. The rays in Fig. 3 are reversed, with ψ and μ again designating the zenith angles of the incident and reflected rays. The radiant flux from a segment of sky S reflected by the unit area A toward the observer O is (in place of eq. 11)

$$N_s\, \rho(\omega) \cos \omega \sec \beta \; p\delta z_x \delta z_y \, ,$$

where N_s is the radiance of the sky (power per unit solid angle per unit area normal to the beam). Summing over all *visible* slopes yields the total reflected flux from the unit area A toward the observer O,

$$\iint N_s\, \rho(\omega) \cos \omega \sec \beta \; p dz_x dz_y \, . \qquad (22)$$

The radiance of the sea surface in the observer's line of sight (intensity per unit area normal to the beam) is found by dividing by $\cos \mu$:

$$N = \sec \mu \iint N_s\, \rho(\omega) \cos \omega \sec \beta \; p dz_x dz_y \, . \qquad (23)$$

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[6] Effectively we write $[N_{s\parallel} + N_{s\perp}]\,[\rho_{\parallel} + \rho_{\perp}]$ (or $N_s\, \rho$ in our notation) instead of $N_{s\parallel}\rho_{\parallel} + N_{s\perp}\rho_{\perp}$, where $\parallel$ $\perp$ refer to polarization in the plane of incidence, and normal to it, respectively.

For the special case of a uniform sky dome, N_s is constant, and the expression for (N/N_s) is identical with that for R in section 3. The preceding remarks on integration limits are applicable, and the results given in equations (15)–(20) and in Figs. 4 and 5 can be applied directly.

For the case where sky radiance depends on the zenith angle ψ (and ψ only), we must generalize the procedure in section 3. Writing the law of reflection in the form (Fig. 3)

$$\cos\psi = \cos^2\beta\,[(1 - \tan^2\beta)\cos\mu + 2z_y \sin\mu], \tag{24}$$

and again expanding in Taylor's series, leads to the integrals in section 3 with R now denoting $N(\mu)/N_s(\psi)$, and with a, b, c replaced by

$$\begin{aligned} a_s &= -F'/F - 2N_s'/N_s\,, \\ b_s &= \tfrac{1}{2} + \tfrac{1}{2}F''/F + 2(N_s'/N_s)(F'/F) + 2N_s''/N_s\,, \\ c_s &= \tfrac{1}{2} + \tfrac{1}{2}(F'/F)\cot\mu + 2(N_s'/N_s)\cot\mu\,. \end{aligned} \tag{25}$$

Fig. 7 shows the results for two sky conditions illustrated in Fig. 6. Directly beneath the observer ($\mu = 0°$), the rough sea may be brighter or dimmer than a smooth sea depending on the condition of the sky. A rough sea contrasts with a flat surface most markedly near the horizon, where the rough sea appears darker. If the sea were absolutely flat, then the radiance of the sea surface just beneath the horizon would equal the radiance of the sky just above it, and there would be no visible horizon.

The albedo of the sea surface exposed to sky light is the ratio of reflected to incident flux. The reflected flux from a unit area is $N(\mu)\cos\mu$ (compare equations 22 and 23) and the total reflected flux is $2\pi\int_0^{\frac{1}{2}\pi} N(\mu)\cos\mu\sin\mu\,d\mu$. Similarly, the total incident flux is $2\pi\int_0^{\frac{1}{2}\pi} N_s(\psi)\cos\psi\sin\psi\,d\psi$. Hence the albedo is given by

$$R = \int_0^{\frac{1}{2}\pi} N(\mu)\sin 2\mu\,d\mu \Big/ \int_0^{\frac{1}{2}\pi} N_s(\psi)\sin 2\psi\,d\psi\,. \tag{26}$$

TABLE I. Albedo of Sea to Sky Light

Sea *Sky*	*Smooth* ($\sigma = 0$)	*Rough* ($\sigma = 0.2$)
Clear	.100	.071 – .088
Uniform	.066	.050 – .055
Overcast	.052	.043 – .044

The albedo has been evaluated numerically for a smooth and rough sea surface for each of the three sky conditions shown in Fig. 6. In the case of the rough surface, the integration was carried out along both branches of the curve $\sigma = 0.2$ in Fig. 7; the correct values are

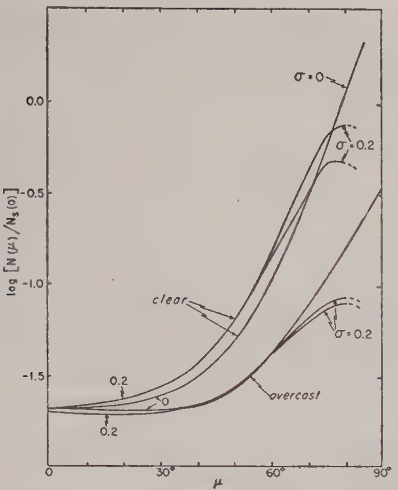

Figure 7. The radiance of the sea surface, $N(\mu)$, divided by the sky radiance at the zenith, $N_s(0°)$, as a function of the vertical angle μ. The curves are computed for a flat ($\sigma = 0$) and rough ($\sigma = 0.2$) surface for each of the three sky conditions illustrated in Fig. 6. The two branches for the curves marked $\sigma = 0.2$ again indicate the upper and lower limits inherent in equations (19) and (20).

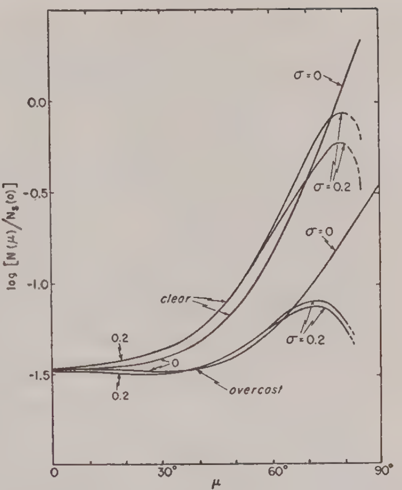

Figure 8. The radiance of a slick sea surface (see legend of Fig. 7).

believed to lie within the indicated limits. Compared to a flat sea, the albedo is reduced by about 20% in the presence of a Beaufort 4 wind, due largely to the hiding of effectively reflecting slopes and to subsequent darkening of the sea surface near the horizon.[7]

For the uniform sky, Schmidt (1915) had previously obtained a theoretical value of 0.17. Measurements by Neiburger (1948) and

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[7] Note added in proof: Burt (1954) has calculated the albedo of the sea surface to direct sunlight and diffused light by methods similar to ours. However, there are two important differences. Burt made no allowance for multiple reflections but he allowed for shadowing by assuming the *same* distribution of slopes in the shadowed and unshadowed areas. For very low sun elevations he obtains 100% effective reflectivity regardless of surface roughness, whereas our approximation indicates a lowering of reflectivity which increases in magnitude with increasing roughness. Applied to the reflection of skylight, Burt's result implies that there would be no contrast at the horizon, while in fact the sea is darker than the sky, particularly on windy days. Fortunately the albedo to skylight is little effected by any of these assumptions. For $\sigma = 0.2$, Burt obtains $R = .058$ (clear sky), .048 (overcast), while our values are .050 — .055 (clear), .043 — .044 (overcast).

Burt (1953) under an overcast sky gave only 0.10. Burt subsequently noticed that Schmidt had omitted cosine terms in his flux intergration. The correct integration, already carried out by Judd (1942), gave a value of 0.066. Whereas initially the theoretical value had been too high, it was now too low with the discrepancy almost as bad. The values in Table I show that allowance for surface roughness does not help. The explanation seems to be the one offered by Neiburger (in press): a reflection from bubbles and particles in the water in addition to the reflection at the surface. The average reflection due to internal scattering measured by Powell and Clarke (1936) is 0.3, and this brings observation and theory into reasonable accord. Our measurements (Cox and Munk, 1954a) also indicate that the scattered intensity can be an appreciable fraction of the reflected intensity.

5. VISIBILITY OF SLICKS

As an application of the preceding section we may consider the contrast of slick streaks on a roughened water surface.

A slick is caused by the presence on the sea surface of a thin layer of organic matter. Natural slicks are often thin compared to the wave length of light, and the reflection coefficient of a slick surface is practically the same as that of an uncontaminated surface. The thin layer becomes visible because the rms slope is substantially smaller there than elsewhere. This reduction is accomplished, at least in part, by the viscous dissipation of wavelets against the quasi-inextensible surface film. The reduction in slope in a good sized slick may be achieved by a factor of 1.5 to 2 (Cox and Munk, 1954b).

A slick lying *within* the sun's glitter pattern has a larger luminosity near the glitter center and a smaller luminosity near the outer edges than the uncontaminated water surface. This has already been discussed (Cox and Munk, 1954b) and an example is shown in fig. 2 of that paper. The visibility of thin (natural) slicks *outside* the sun's glitter can be discussed with reference to Fig. 7. To an observer looking steeply downward (small μ), the slick (small σ) appears dark under a clear sky, light under an overcast sky. Near the horizon the slick is always light. The contrast required for the visibility of large slicks is of the order of 2% ($\sim$ 0.01 on the logarithmic scale in Fig. 7), and we may expect adequate contrast for visibility even when the winds are light. In searching for thin slicks one should concentrate on an area well toward the horizon in clear weather.

The situation is different in the case of freshly spread slicks of mineral oil. The presence of interference colors demonstrates a thickness larger than a wave length of light. Suppose the index of refraction is that of light oil, $n = 1.45$, as compared to 1.34 for water.

For normal incidence the reflectivities are

$$(n - 1)^2 (n + 1)^{-2} = 0.034 \text{ for air-oil interface,}$$
$$= 0.020 \text{ for air-water interface.}$$

Multiple reflections within the oil layer increase the effective reflectivity to 0.036, 1.8 times that of an uncontaminated surface. The ratio is smaller for glancing incidences. It equals 1.6, 1.3, 1.0 for angles of incidence 30°, 60°, 90°.

These coefficients have been taken into account in Fig. 8. The visibility of thick (artificial) slicks can be estimated by comparison with Fig. 7. Suppose we compare the oily smooth surface (Fig. 8, $\sigma = 0$) with the uncontaminated rough surface (Fig. 7, $\sigma = 0.2$). The slicks are brighter, and the contrast is most marked directly beneath the observer ($\mu = 0°$).

Some remarkable photographs of slick bands have been published by Ewing (1950). The surprising aspect is that these bands are due to *internal* waves. These are made visible by a curious chain of events: the orbital motion of the internal waves converges at the troughs and the oils resulting from biological activity are squeezed into a surface-active film under tension, as shown by Ewing. This film, by virtue of its resistance to stretching, imposes a horizontally quasi-rigid boundary against which short wavelets generated by local winds dissipate most of their energy. The resulting decrease in mean square slope affects the average reflectivity and also the segment of sky that is mirrored in the trough zones; both of these effects produce a brightness contrast between the slicks and the surrounding ruffled water. It would seem that it is virtually impossible to predict the devious means by which nature chooses to reveal herself to the astute observer!

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Early Developmental Stages of the California Scorpionfish, *Scorpaena guttata*

GRACE L. ORTON

THE California scorpionfish, *Scorpaena guttata* Girard, spawns throughout the summer months in aquaria at Scripps Institution. Captive specimens have supplied material for studies on the eggs and early larval stages of this marine species by Barnhart (1932) and David (1939), as well as for the present paper. In the work reported here, the embryonic and prolarval stages are re-described in greater detail in an effort to simplify future comparison with the early pelagic stages of other scorpaenid fishes of the Pacific coast. The eggs and newly hatched larvae from Cortez Banks that Eigenmann (1892) tentatively identified as *Fierasfer dubius* are here referred to *Scorpaena* sp. In addition, the literature on early stages of several extra-limital forms of *Scorpaena* and of certain other fishes is discussed briefly, and the need for more extensive study of developmental characters of scorpaenid fishes is pointed out. The description of *S. guttata* is based on living specimens except where otherwise stated.

This paper is No. 777 in "Contributions from the Scripps Institution of Oceanography, New Series."

EGGS

The general appearance of the egg mass of *Scorpaena guttata* is well known from the descriptions by Barnhart and by David. The eggs are imbedded, each in a cell-like space, in a single layer in a thin gelatinous matrix that forms a hollow, bilobed balloon. The mass has a length of about 250 mm., and drifts at or near the surface until the eggs hatch. Individual eggs, freed from the gelatinous material, also float at the surface. When freshly spawned, both the matrix and the eggs are colorless, transparent, and very inconspicuous in the water, but the matrix ultimately acquires a somewhat milky appearance.

The recently spawned egg mass is a remarkably elastic unit. In microscopic examination with oblique light, fresh pieces show series of very minute surface striations which change in shape and spacing when the matrix is stretched or pulled, and are probably associated with the elastic structure of the material. The texture of the matrix changes considerably during incubation. At three days, the tiny surface striations are no longer visible, and the material is softened and invaded throughout by microorganisms, which form minute whitish flecks. On the surface, these microorganisms concentrate along sutures that outline polygonal blocks of irregular size and shape, one enclosing the position of each egg (Fig. 1). These structural details, not previously described for this species, suggest that the matrix is at least partly compounded from material secreted around each individual egg. Sparta (1928) found a similar block-like construction to characterize a gelatinous pelagic egg mass of an unidentified Mediterranean scorpaenid.

The individual egg of *Scorpaena guttata* is slightly ovoid and has a long diameter of about 1.2 mm. The thin capsule and the yolk are transparent, colorless, and non-textured. There are no oil globules, and there is no visible perivitelline space until the embryo is sufficiently developed to indent the surface of the yolk away from the capsule.

EMBRYONIC DEVELOPMENT

Some of the principal events in the embryology of *Scorpaena guttata* were stated briefly by David (1939). She found that freshly spawned eggs were always in "advanced blastoderm" stage when taken from the tanks in the morning, and she estimated that spawning occurs about midnight. Twenty-two hours after this estimated time of fertilization, the blastoderm enclosed about four-fifths of the yolk and an embryonic axis with seven somites had formed; at 34 hours the blastopore had apparently closed, there were 14 somites, the eyes, lenses, and ear capsules were formed, and Kupffer's vesicle was present, but pigment had not yet appeared. Some of the embryos, she recorded, hatched at an estimated age of about 58 hours, but "most hatch during the following night."

In the material I have studied, freshly spawned eggs taken from the tanks early in the morning have been in blastular stages, essentially as reported by David. The blastular cap covers one end of the yolk and has a minutely granular texture. Around its periphery the cells are larger and very distinct. On the yolk surface, a short distance out from the defined blastular margin, there is a conspicuous zone of linear, granular objects that appear to be large cells (periblast nuclei?) that are migrating outward.

Embryos in later stages of germ ring growth and blastopore closure show progressive advances in differentiation of the embryonic axis and of its associated structures. The brain is slightly widened and the optic capsules are defined, but the lenses are not yet visible. An embryo with a very large blastopore appeared to lack defined somites; one with a small blastopore had about six somites and a distinct Kupffer's vesicle. Embryos with the blastopore closed but with a scar-like area still marking its position have nine or ten somites. In these embryos, the body axis extends nearly the full length of the yolksac, and ear capsules are distinct. This stage is developmentally younger than David's 34-hour embryo. After closure of the blastopore, the surface of the yolksac has a slightly pebbled texture which apparently results from the presence of enlarged cells scattered in the skin. The yolk itself remains homogeneous and non-textured. Kupffer's vesicle is often complex in this species, as noted by David. In some embryos it consists of a cluster of seven or more bubble-like expansions, with one larger than the rest.

On the morning after closure of the blastopore (age about 36 hours), the body is well defined and slight movements are occasionally visible. There are apparently about 23 somites (about 12 on the body and about 11 on the short tail). The lenses have formed and the small ear capsules are better defined. The heart has formed, in line with the posterior end of the midbrain, and it contracts occasionally. The median finfolds are distinct, the dorsal fold visible at least as far forward as the midbrain. The perivitelline space is evident anteriorly and caudally, where head and tail depress the surface of the yolksac away from the capsule. A few hours after this stage, the tail has lengthened distinctly and has a greater lateral curvature, and the dorsal finfold is better defined anteriorly, where it now rises well above the underlying tissues.

The next morning (age about 56 hours, in David's method of timing) some of the eggs hatch if they are shaken. At this stage (Fig. 2) the embryo has well-developed median finfolds; anteriorly, the dorsal finfold has inflated, baglike contours and does not form a median edge. Reduction of the yolk has begun, but there has not been a corresponding shrinkage of the skin overlying it; hence the peculiar ballooned appearance of the yolksac. The heartbeat is fairly regular at this stage. The tail curves laterally, but is too short to reach the head. The anal tube adjoins the posterior surface of the yolksac. Some embryos, apparently normal, remain encapsuled for as long as 24 hours after most of the individuals have emerged. The actual process of hatching has not been observed, and it is not certain how these small, delicate larvae escape from the thin but extremely viscid matrix in which the eggs are imbedded. Under laboratory conditions, the matrix becomes heavily infested with microorganisms and partly disintegrates before hatching occurs.

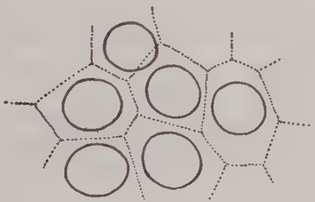

Fig. 1. Part of egg mass of *S. guttata*, diagrammed to show polygonal surface texture of matrix.

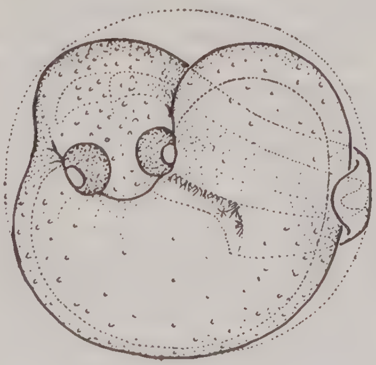

Fig. 2. Advanced embryo of *S. guttata*.

The Prolarval Stage

As defined by Hubbs (1943), the prolarval stage of fishes comprises the period in larval development from hatching to the complete disappearance of the yolksac. The newly hatched prolarva of *Scorpaena guttata* (Fig. 3) was described briefly by both Barnhart (1932) and David (1939), and was figured by the former. Larvae that hatch at the average time (about three days) have a total length of about 1.9 to 2.0 mm. The larva is transparent, and is moderately stout-bodied and short-tailed. The transparent, colorless yolksac is large and ovoid, but usually extends forward no farther than the posterior edge of the eye. The gut is well developed, straight, rather flat except posteriorly; the hindgut is curved downward, and the anus is slightly posterior to the end of the yolksac. The head contours are still very embryonic; the eyes are well developed, but there are no visible jaws. The tail is well developed, and is slightly shorter than the head and body. The tail tip is straight and simple, with no indication of hypural, or ray development. The pectoral finbuds are small and inconspicuous; there is no trace of pelvic buds or of median finrays. The skin over all surfaces is much inflated and bag-like; it closely adjoins the subsurface structures at only a few points, chiefly at the tip of the snout and in the pectoral region. The dorsal finfold has a broad transverse curvature anteriorly, and bears a median longitudinal zone of somewhat enlarged cells; only along the distal part of the tail is the finfold compressed to form a distinct edge. "Ballooning" of the skin is especially conspicuous around the yolksac. The entire surface of the skin is slightly roughened by minute, widely spaced granulations. After preservation in formalin, the wide mid-dorsal surface of the dorsal finfold acquires the hexagonally patterned texture figured by both Barnhart and David. Preservation apparently emphasizes the outlines of the enlarged skin cells in this area. The eyes of the recently hatched larva are dark gray. There is a double row of finely dendritic melanophores along the top of the gut, with branching processes that extend upward along the bases of the somites and downward over the sides of the gut; there are a few melanophores along the lower surfaces of the gut.

The macroscopic appearance of the larvae at this stage was aptly described by Eigenmann (1892: 173) as "sets of two black dots and a black streak." His drawings, though diagrammatic, show the pigmentation of the advanced embryo and hatching larva of *Scorpaena* more accurately than does Barnhart's figure of the same stage.

On the following day (about 72 hours after estimated spawning time) most of the larvae have hatched. The reduced yolksac varies somewhat in size and shape, and is placed well back along the gut. The rather posterior position of the yolksac and the extension of the dorsal finfold forward onto the front of the head combine to give the head a somewhat overbalanced appearance at this stage (Fig. 4). The pectorals are larger and are edged with a thin finfold. The head contours are considerably modified, for the midbrain now bulges upward and forward and the jaw and branchial rudiments form a prominent swelling on the lower surface of the head. The somites are difficult to count, but appear to number $10 + 14 = 24$ (the adult has 24 vertebrae; Clothier, 1950). The eyes are black with a few iridescent greenish flecks, and the melanophores on the gut are more abundant and cover the adjacent surfaces of the somites and the yolksac more extensively. Some of the larvae now have a few very small melanophores along the midventral edge of the tail.

Three days later (four days after average hatching time) the yolk appears to be nearly or entirely gone, and the gut is much larger. The jaws are well developed and functional, and the head is proportionally much larger than

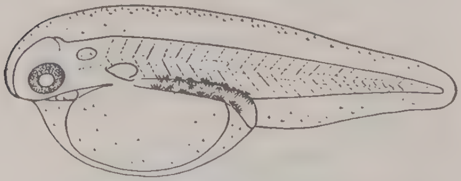

Fig. 3. Recently hatched larva of *S. guttata*.

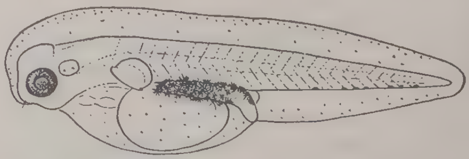

Fig. 4. Larva of *S. guttata* about one day after hatching.

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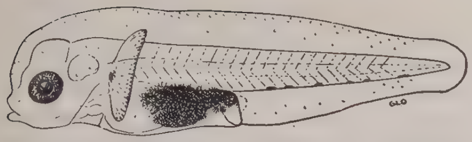

Fig. 5. Larva of *S. guttata* about four days after hatching.

in earlier stages (Fig. 5). The median finfolds and the skin over the body are still bag-like except on the posterior part of the tail where the finfolds form thin, compressed edges. Around the eyes and the jaw region the skin is closely attached to the subdermal tissues. The inflated skin perhaps aids in flotation. The median finfolds are still simple, non-rayed. The very large, fan-shaped pectoral fins are now important in locomotion. They beat strongly with appropriate action for forward swimming, backing, and turning, and when at rest they are held stiffly at nearly a right angle to the body. The larva is still transparent, and its basic pigmentation is little changed. The jet black eyes have flecks of iridescent bronze pigment. The posterior half of the body cavity has become more densely covered with melanophores, and a few small ones have appeared internally in the region of the pectoral girdle. The pectoral fins are edged with from one to several irregularly defined rows of very small melanophores. Some of the larvae have a large stellate melanophore on the base of the pectoral. The row of small black cells along the midventral edge of the tail persists without apparent change.

The larvae seem to be quite hardy, even in small, crowded containers; but thus far all efforts to induce them to feed have failed, and it has not been possible to keep them alive in the laboratory for much longer than this stage.

COMPARISONS

The eggs, embryos, and early larvae of *Scorpaena guttata* are of striking appearance, and are easily distinguished from described stages of other fishes of the California coast; but it should be emphasized that the life histories of the marine fishes of this region are still very inadequately known. The California scorpaenid fauna also includes two species of *Sebastolobus* and about 50 forms of the complex genus *Sebastodes*. So far as known, the species of *Sebastodes* are live-bearing and produce large "litters" of very small larvae. The few of these larvae that have been described, and those that I have seen, show a close group resemblance to *Scorpaena* in general morphological characters, but too few of them are known to justify detailed comparisons at present. Apparently nothing has been published on the reproduction of *Sebastolobus* or on its early developmental stages. Detailed comparative studies on the development of the Pacific coast scorpaenids are much needed, both for taxonomic purposes and for increased knowledge of the ecology of these desirable food and sport fishes.

Little has been published on early stages of extra-limital species of *Scorpaena* except those in the Mediterranean, although the genus has a nearly worldwide distribution in coastal waters of tropical and temperate seas. Early stages of *Scorpaena porcus* Linnaeus were described by Raffaele (1888), Fage (1918), and Sparta (1941a); of *S. scrofa* Linnaeus by Raffaele (*op. cit.*), Fage (*op. cit.*), and Sparta (1941b); of *S. ustulata* Lowe by Sparta (1941b); and of *Scorpaena* (*Helicolenus*) *dactyloptera* Delaroche by Fage (*op. cit.*) and Sparta (1941b). In addition, Sparta (1941a, b) discussed the possibility that the unidentified egg mass and larvae that he had described earlier (1928) might be referable to *S. dactyloptera*. The larvae that hatched from these eggs agreed closely in general characters and pigmentation with the smallest larvae of a developmental series of *dactyloptera* collected in the Straits of Messina, but differed in having a higher somite count (27–29) than the 24 or 25 thought to be typical of *Scorpaena* (including *Helicolenus*), and the eggs possessed an oil globule, which is lacking in the few definitely known eggs of *Scorpaena*.

The references cited above record specific differences in details such as egg size and larval pigmentation, but these Mediterranean forms agree closely among themselves and with *Scorpaena guttata* in the type of egg mass and in the general morphology and pigmentation of the embryo and larva. So far as the life histories of these fishes are known, the general pattern of development is essentially the same in the Mediterranean as it is in California waters. The consistent group resemblance in basic characters between geographically remote populations is more significant for studies in the developmental systematics of these fishes than are the relatively small specific differences. Similar examples of stability and predictability of basic developmental characters should be made more generally known to fish taxonomists, in order to stimulate wider use of (and greater willingness to trust) this rich source of data for systematic studies.

Egg masses with a loose, gelatinous texture are known in relatively few groups of fishes, but eggs of this type characterize several groups that have representatives along the Pacific North American coast. Several of the Atlantic pediculate fishes, including *Lophius* and *Histrio* [*Pterophryne*], are known to have large, flat, ribbon-like, pelagic egg masses (Gudger, 1937), and it seems likely that forms of the related *Antennarius* along the Pacific coast may be similarly characterized. Two Mediterranean cusk-eels of the blennioid family Ophidiidae, *Ophidium barbatum* and *O. vassalli*, are reported to have small pelagic egg clusters (Sparta 1929). It is possible that similar egg masses may characterize some of the cusk-eels of the Pacific coast, but individual pelagic eggs have been taken off La Jolla that hatch into larvae which are not essentially different from described ophidiid larvae (unpublished notes).

The eggs of the Mediterranean *Carapus acus*, described by Emery (1880) under the name *Fierasfer acus*, are deposited in small, ellipsoidal, gelatinous, floating masses with dimensions of about 83 × 40 mm. The individual egg has a slightly ovoid shape, with a long diameter of 0.9 mm., and there is a large oil globule. In the newly hatched prolarva a small knob-like structure breaks the outline of the dorsal finfold a little posterior to the middle of the trunk. Soon after hatching, this structure begins to enlarge, and within a few days it forms a long filamentous ray with a series of heavily pigmented leaf-like appendages. The entire ray becomes nearly as long as the larva.

It seems probable that the eggs which Eigenmann (1892) identified tentatively as *Fierasfer* [*Carapus*] *dubius* were, instead, a species of *Scorpaena*. The size of the transparent, jelly-like mass (about one-half pint), the arrangement of the eggs in a single layer, the structure and pigmentation of the advanced embryos and hatching larvae, and the absence of oil globules agree essentially with diagnostic characters of *Scorpaena*. Eigenmann's figure of the prolarva (his pl. 16, fig. 8) was based on a somewhat distorted, preserved specimen, but it shows no indication of the developing dorsal filament of the carapid larva. The eggs were rather small (diameter only 0.8 mm.), and it seems possible that they were spawned by some other northward-ranging species of *Scorpaena* rather than by *S. guttata*. Scorpionfishes are definitely known to occur on Cortez Banks, but there appear to be no valid records of carapid fishes that far north. Thus far, I have found no published information on the eggs or young larvae of any of the carapid fishes of the eastern Pacific.

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Thorium Determinations in Manganese Nodules

A knowledge of the geochemical behavior of thorium isotopes in the sedimentary cycle is a prerequisite in using the ionium decay scheme for the measurement of the rates of accumulation of deep-sea sediments. Inasmuch as manganese nodules may reflect mainly hydrogenous precipitation processes (*1*), it was felt of interest to measure their thorium content. Previously, Matthews (*2*) reported evidence for the enrichment of thorium in manganese nodules with respect to pelagic clays. Thorium in pelagic clays averages 5 ppm (*3*), whereas Matthews reports minimum thorium contents in three nodules of 30 to 40 ppm. Koczy (*4*) had previously observed higher values of thorium in the nodules than in clays with lower absolute values in both cases.

The following method was employed. Complete dissolution of approximately 1 g of the sample is accomplished by HCl-$HClO_4$, followed by a HF dissolution of the silica residue and a sodium carbonate fusion of any remaining solids. Thorium-234 is added to the combined solutions as a tracer for the determination of the yield. The thorium is then coprecipitated with $Fe(OH)_3$ upon addition of gaseous ammonia. The precipitate is dissolved in HF, and lanthanum carrier is added to precipitate LaF_3, which coprecipitates the thorium. This step is repeated to insure a complete separation of thorium from zirconium. The precipitate is dissolved in an aluminum nitrate-nitric acid solution, and the thorium is extracted into mesityl oxide (*5*). The thorium is stripped into water and extracted into a 2-thenoyltrifluoro acetone (TTA)-benzene mixture (*6*). The residue is then taken up in HCl and measured colorimetrically as the "thoron" complex of thorium (*7*).

The yields varied between 50 and 80 percent. Blank values on the reagents were less than 0.1 μg of thorium. The main interference in the colorimetric method comes from zirconium. Spectrographic analyses on the final residue from the TTA-benzene extraction revealed that the zirconium concentrations were below interfering levels.

The analyses of a number of Pacific Ocean manganese nodules are given in Table 1. Thorium is concentrated in manganese nodules by factors exceeding 5 over deep-sea sediments. This elemental enrichment of thorium closely parallels manganese. Such a result is not unexpected, since other elements, probably existing as cations in sea water, such as nickel, copper, and lead, show a similar behavior (*1, 8*). The unusually high thorium content of the Horizon nodule is anomalous. The thorium was not enriched either in the acid-insoluble residue or in the zeolite phases that form the core of the nodule and often accompany the manganese phases.

These preliminary results (*9*) lend support to the ionium-thorium method for the determination of the rates of accumulation of deep-sea sediments (*3*), since one of the major assumptions of this method is that ionium and thorium in the sediments are accumulated from sea water as opposed to volcanic or terrestrial sources.

Table 1. The thorium contents of manganese nodules from the Pacific Ocean.

Nodule	Latitude	Longitude	Depth (fathoms)	Thorium (ppm)
Horizon nodule	40°14′N	155°05′W	2790	124 ± 15
Cape Johnson Gyot	17°10′N	177°10′W	1055–1120	24 ± 5
Gulf of Alaska, sample 3	56°10′N	145°15′W		25 ± 2
Hess Guyot (manganese coatings on coquina shells of *Vermicularia*)	17°54′N	174°16′W	956–80	30 ± 6

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16 February 1955.

ECOLOGY OF FORAMINIFERA IN SOUTHEASTERN MISSISSIPPI DELTA AREA

BY

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Reprinted for private circulation from
The Bulletin of the American Association of Petroleum Geologists
Vol. 39, No. 5, May, 1955

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BULLETIN OF THE AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS
VOL. 39, NO. 5 (MAY, 1955), PP. 712-752, 40 FIGS.

ECOLOGY OF FORAMINIFERA IN SOUTHEASTERN MISSISSIPPI DELTA AREA[1]

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ABSTRACT

1. The Foraminifera are grouped into three principal biofacies and one subfacies in the Mississippi Delta area.
   a. The following species are confined to the marsh facies.
      Ammoastuta inepta (Cushman and McCulloch)
      Arenoparrella mexicana (Kornfeld)
      Leptodermella variabilis Parker
      Miliammina fusca (H. B. Brady)
      Trochammina macrescens H. B. Brady
   b. The Breton Sound facies is characterized by the abundance of various species of *Ammobaculites*, and also by *Ammoscalaria pseudospiralis* (Williamson) and *Gaudryina exilis* Cushman and Bronnimann. *Elphidium incertum mexicanum* Kornfeld and *E. matagordanum* (Kornfeld) also are largely confined to this facies.
   c. The open-gulf facies is characterized by the following species.
      Bigenerina irregularis Phleger and Parker
      Bolivina lowmani Phleger and Parker
      Buccella hannai (Phleger and Parker)
      Buliminella cf. *bassendorfensis* Cushman and Parker
      Cibicidina strattoni (Applin)
      Epistominella vitrea Parker
      Nonionella atlantica Cushman
      N. opima Cushman
      Nouria polymorphinoides Heron-Allen and Earland
      Proteonina atlantica Cushman
      P. sp. A
      Virgulina pontoni Cushman
   d. The offshore "subfacies" is characterized by the following species which are either restricted to it or occur there in greater abundance than elsewhere.
      Bigenerina irregularis Phleger and Parker
      Cibicidina strattoni (Applin)
      Epistominella vitrea Parker
      Nouria polymorphinoides Heron-Allen and Earland
      Proteonina atlantica Cushman
2. Facies transition areas
   a. The average boundary between the open-gulf and Breton Sound facies extends south from Breton Island to Main Pass. There is a mixing of many typical open-gulf and Breton Sound species through a zone 10–15 miles wide extending on either side of this boundary.
   b. The bays and other nearshore areas contain a Breton Sound fauna with marsh species.
3. a. Distribution of the living population of the various species seems to show good correlation with the distribution of the dead population. This suggests little large-scale post-mortem transportation of the tests.
   b. The total living population varies from 1116/sample to 0/sample. The northernmost area generally has the smallest standing crop of Foraminifera, approximately 10–50/sample,

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[1] Contribution No. 19, Marine Foraminifera Laboratory; Contribution No. 779, Scripps Institution of Oceanography. Manuscript received, February 7, 1955.

[2] Marine Foraminifera Laboratory, Scripps Institution of Oceanography.

The writer is grateful to the staff of American Petroleum Institute Project 51 who collected these samples and made them available for study. Special thanks are due to P. C. Scruton who organized the work in the Mississippi Delta area and who has made numerous suggestions to the writer, and also for permission to use Figures 1–3. Figure 4 is used through the courtesy of D. G. Moore and R. H. Parker. Analysis of the samples was done by Jean F. Peirson. William R. Walton and Frances L. Parker reviewed the manuscript. The laboratory work was supported by the Office of Naval Research, under Contract Nonr-23301, and by American Petroleum Institute Project 51.

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the middle area averages approximately 100/sample, and the largest living populations occur at the inshore open-gulf stations.

c. The per cent ratios between living and total populations are grouped into four types of frequency areas. These show a general correlation with presumed sedimentation rates.

4. It is believed that the distributions of the Foraminifera facies in this east delta area reflect the average distributions of the open gulf, Breton Sound, and marsh-river water masses.

INTRODUCTION

This is one of a series of reports dealing with various aspects of the sediments and oceanography of the nearshore area on the southeastern Mississippi Delta in connection with American Petroleum Institute Project 51. The purposes of this report are: (1) to describe the distribution patterns of the Foraminifera in this area and (2) to attempt to interpret these distributions in terms of what is known of environmental factors in this area and of distributions in other areas.

The fauna of this area is closely related to that described from Mississippi Sound and environs in a previous issue of this *Bulletin* (Phleger, 1954). Most of the species are duplicated in the two areas, although the distributions differ in some respects. Reference should be to the previous paper for illustrations of species recorded here (*op. cit.*, Pls. 1–3).

LOCATIONS OF STATIONS AND DESCRIPTION OF AREA

The area sampled is in the southeastern Mississippi Delta region from approximately 29°35′ N. Lat. to 29°05′ N. Lat., and from approximately 88°55′ W. Long. to 89°30′ W. Long. It extends from Pass a Loutre on the south to Breton Sound on the north. This is a part of the rather wide innermost continental shelf which borders the Mississippi Delta on the east. Depths at all stations except those farthest offshore are less than 10 fathoms (60 feet) and many of the depths are only a few feet in Breton Sound and the bays (Figs. 1–2). Seaward (east and south) from the 10-fathom curve the slope of the continental shelf steepens relatively abruptly so that the outer part of the shelf is narrow. The delta shoreline is an irregular one of grassy marsh and there are no sand beaches along this part of the mainland coast. There are numerous delta distributaries entering the area, the two principal ones being Main Pass and Pass a Loutre.

Breton Island lies approximately 8 miles north of Main Pass and is a low island composed largely of sand. Breton Sound lies shoreward from Breton Island, and is connected with the open gulf by a wide inlet on the south. Open-gulf water also has access to Breton Sound through an inlet on the north side of Breton Island.

The following oceanographic description is generalized and is based on studies by P. C. Scruton who will publish a detailed report at a future date. This is included here because of apparent relationships to the Foraminifera facies.

This is an area where there is mixing of open Gulf of Mexico water with fresh water brought in by the Mississippi River. Generally, undiluted open-gulf water may be recognized by a chlorinity of 19 °/₀₀ to 20 °/₀₀. Figure 1, the distribution of surface and bottom chlorinity during a time of average river discharge, shows

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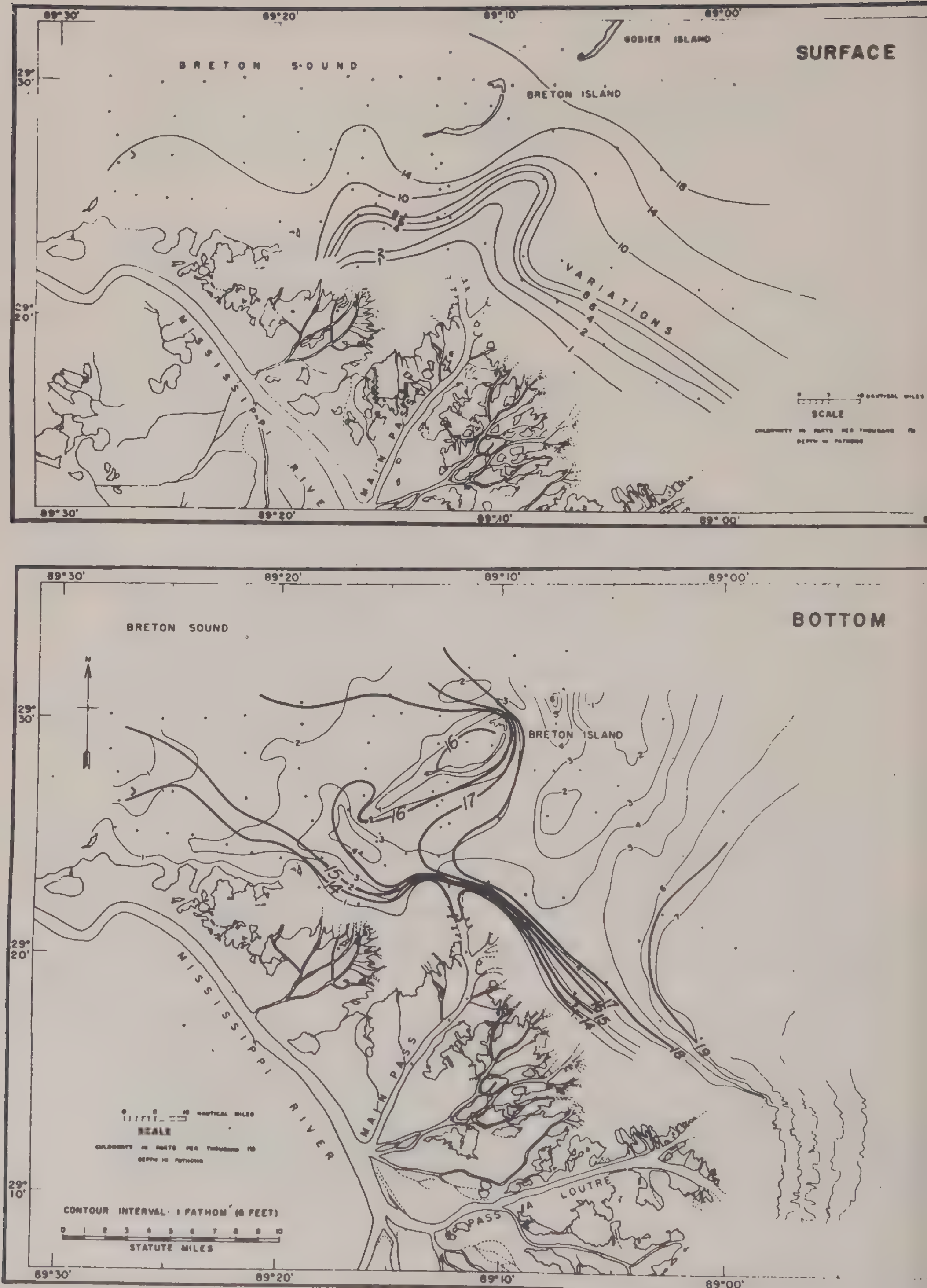
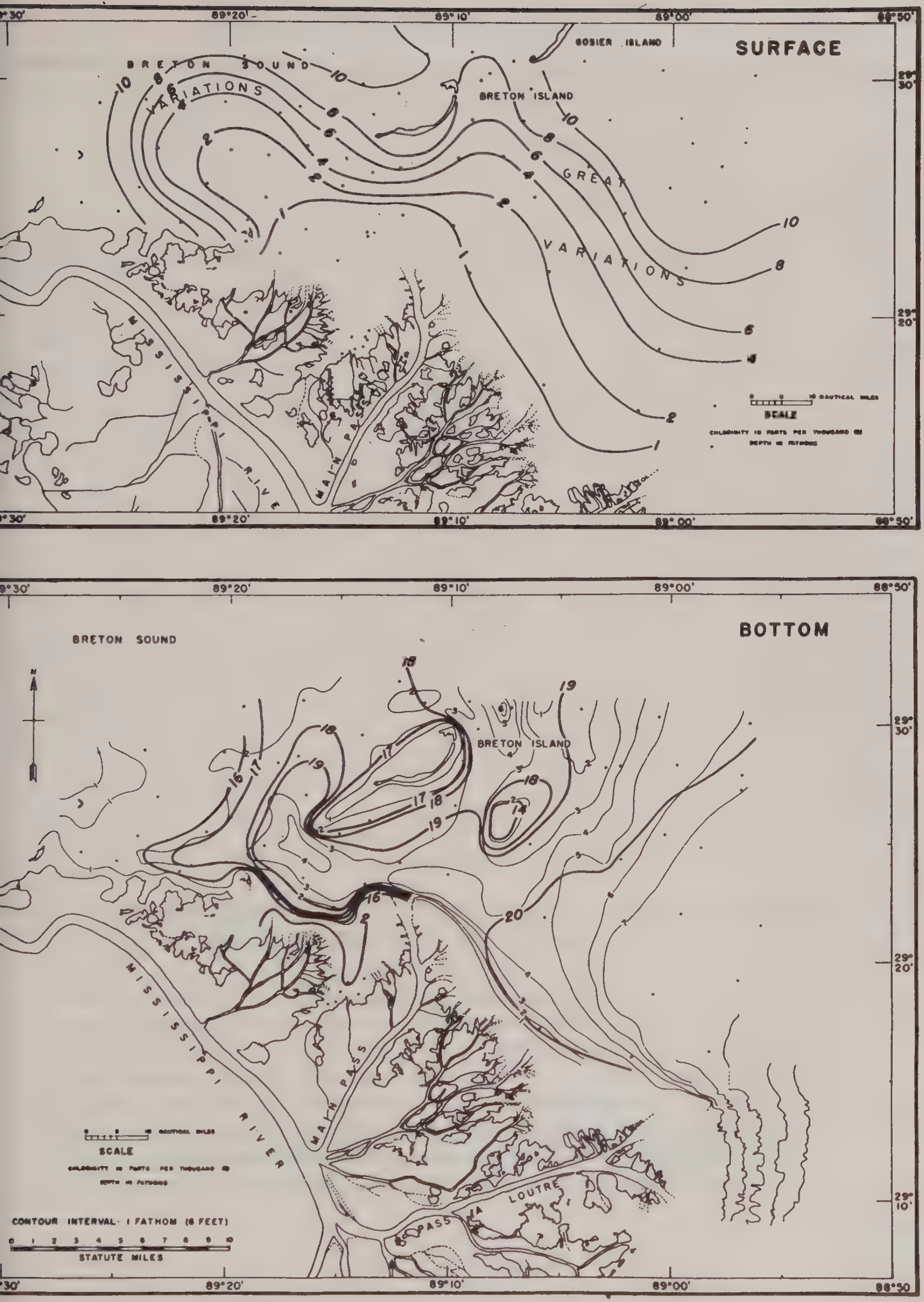

SURFACE
89°30'
89°20'
89°10'
89°00'
29° 30'
29° 20'
BRETON SOUND
GOSIER ISLAND
BRETON ISLAND
MISSISSIPPI RIVER
MAIN PASS
VARIATIONS
18
14
10
8
6
4
2
1
0 5 10 NAUTICAL MILES
SCALE
CHLORINITY IN PARTS PER THOUSAND
DEPTH IN FATHOMS
BOTTOM
89°30'
89°20'
89°10'
89°00'
29° 30'
29° 20'
29° 10'
BRETON SOUND
BRETON ISLAND
N
MISSISSIPPI RIVER
MAIN PASS
PASS A LOUTRE
16
17
15
14
18
19
1
2
3
4
5
6
7
0 5 10 NAUTICAL MILES
SCALE
CHLORINITY IN PARTS PER THOUSAND
DEPTH IN FATHOMS
CONTOUR INTERVAL · 1 FATHOM (6 FEET)
0 1 2 3 4 5 6 7 8 9 10
STATUTE MILES

FIG. 1.—Distribution of surface and bottom chlorinity during fall, 1951. Average river discharge; winds variable. After P. C. Scruton.



SURFACE
BRETON SOUND
VARIATIONS
CHANDELEUR ISLAND
BRETON ISLAND
GREAT
VARIATIONS
MISSISSIPPI RIVER
MAIN PASS
10
8
6
4
2
1
SCALE
CHLORINITY IN PARTS PER THOUSAND IN
DEPTH IN FATHOMS
89°20'
89°10'
89°00'
88°50'
29°30'
29°20'
BOTTOM
BRETON SOUND
BRETON ISLAND
N
16
17
18
19
20
14
MISSISSIPPI RIVER
MAIN PASS
PASS A LOUTRE
SCALE
CHLORINITY IN PARTS PER THOUSAND IN
DEPTH IN FATHOMS
CONTOUR INTERVAL 1 FATHOM (6 FEET)
0 1 2 3 4 5 6 7 8 9 10
STATUTE MILES
29°10'

Fig. 2.—Distribution of surface and bottom chlorinity during spring, 1952. High river discharge; winds low. After P. C. Scruton.

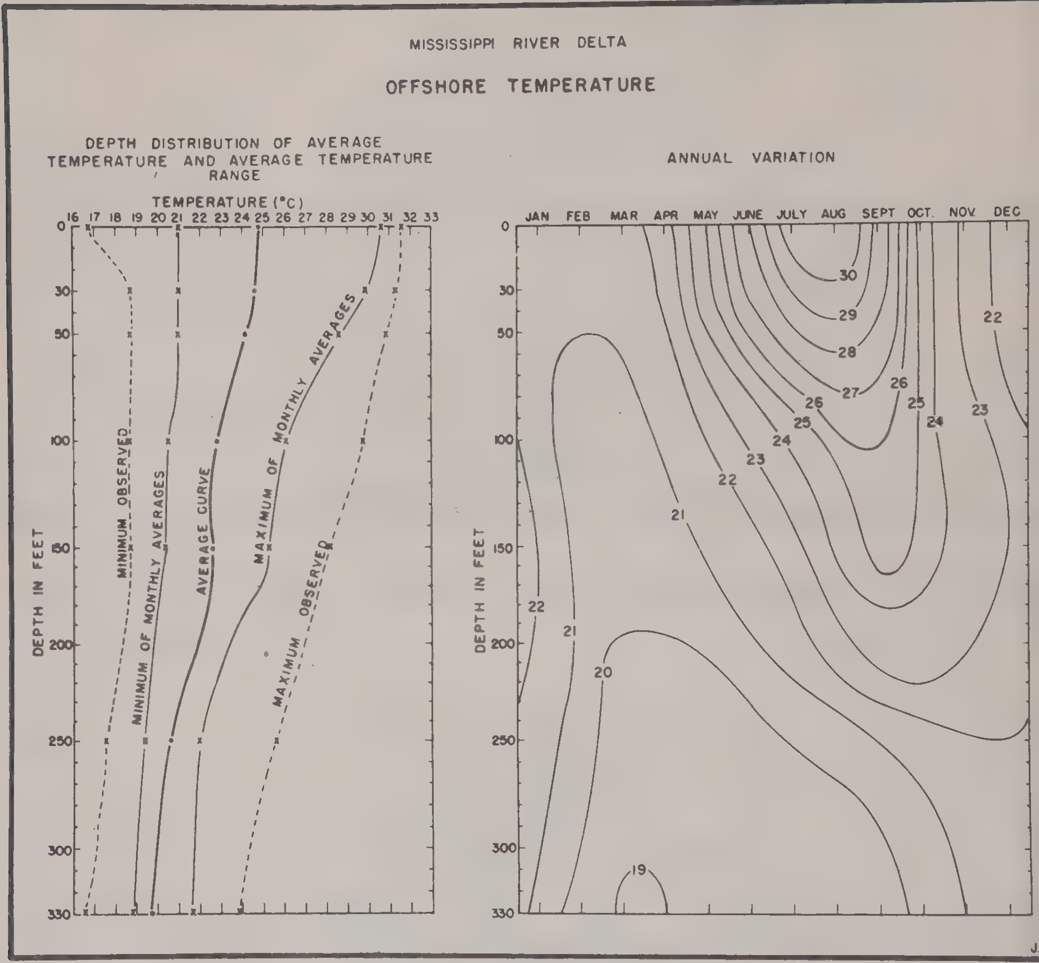


FIG. 3.—Generalized offshore temperatures. After P. C. Scruton.

slightly diluted open-gulf water on the bottom within Breton Sound. This bottom water becomes progressively more dilute shoreward and off the mouths of distributaries where bottom chlorinities of 14 ‰ are recorded. Lower chlorinity water overrides the denser bottom water. During the time of average river discharge in the fall of 1951 the surface chlorinities (18 ‰) were nearly the value for open-gulf water at a distance of about 10 miles off Main Pass. In the northern part of Breton Sound the water was essentially isohaline with depth.

During the spring of 1952, when there was a high river discharge the surface

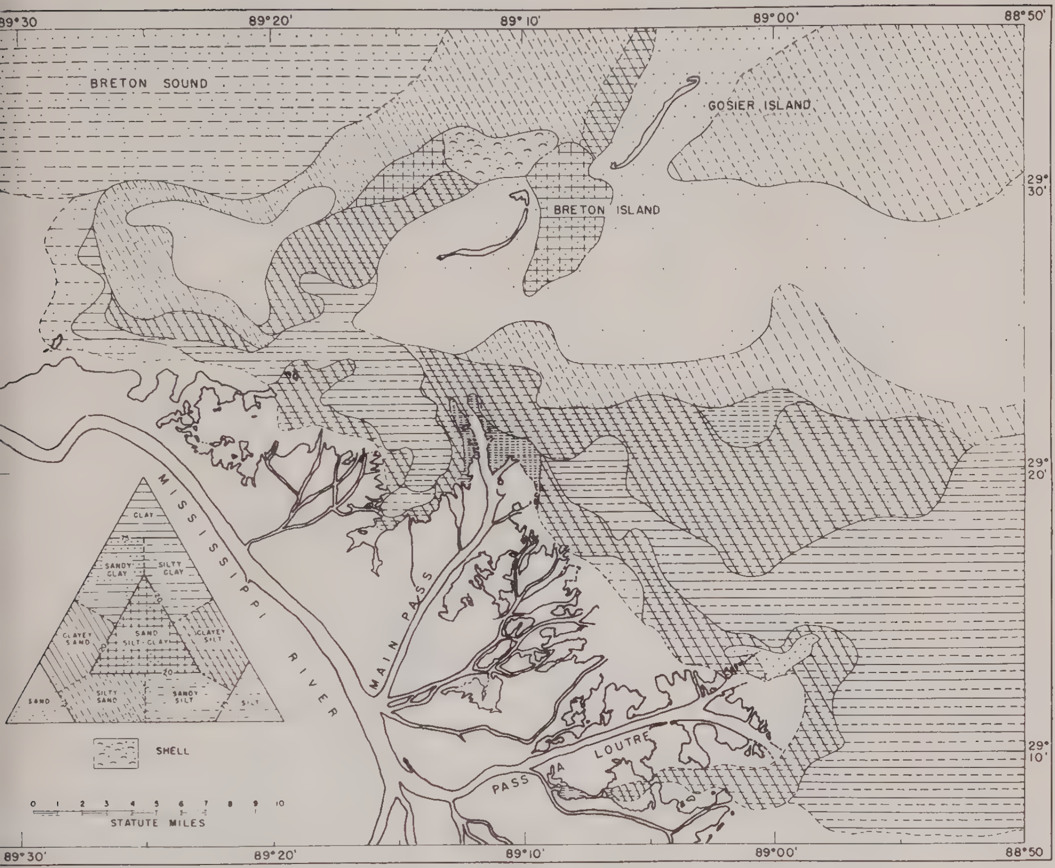

89°30
89°20'
89°10'
89°00'
88°50'
BRETON SOUND
GOSIER ISLAND
BRETON ISLAND
29° 30'
29° 20'
29° 10'
MISSISSIPPI RIVER
MAIN PASS
PASS A LOUTRE
CLAY
SANDY CLAY
SILTY CLAY
CLAYEY SAND
SAND SILT-CLAY
CLAYEY SILT
SAND
SILTY SAND
SANDY SILT
SILT
SHELL
0 1 2 3 4 5 6 7 8 9 10
STATUTE MILES
89°30'
89°20'
89°10'
89°00'
88°50

FIG. 4.—Distribution of sediments in terms of sand, silt, and clay ratios. After R. H. Parker and D. G. Moore.

chlorinities were much lower (Fig. 2). At a distance of 10 miles offshore chlorinities of approximately 10 ‰ were recorded, and similar ones in the inner part of Breton Sound. The chlorinities of the bottom water, however, were approximately the same as those during the previous period of lower runoff, showing the continued invasion of open-gulf water along the bottom.

Figures 1 and 2 give only a general picture of chlorinities in this area. There are numerous short-period variations which may be rapid and of large magnitude. In addition, during times of very high runoff it is to be expected that low-chlorinity water may extend to the bottom in Breton Sound and the inshore area. It is expected that there are times when essentially undiluted open-gulf water extends all over the bottom of Breton Sound and other times when only low-chlorinity water is present. In general, Breton Sound water may be described as an intermediate water mass formed by mixing of river and open-gulf water, and it is subject to large and frequent variation in chlorinity. At a depth of approximately 50 feet the chlorinities are less variable and within the open-gulf range.

Water temperatures also are variable, especially in the inshore area depending on the air temperature, wind force and direction, and temperature of the runoff water. Figure 3 shows the maximum, minimum, and average offshore temperatures, and the annual variation. The minimum offshore surface temperature observed was a little less than 17°C. and the maximum was more than 31.5°C. The extreme observed range at a depth of 30 feet is from 19°C. to 31°+C. In the inshore, shallow areas the variations are more intense because of less water depth and more runoff effect. In the fall of 1951, for example, observed inshore temperatures varied from 10°C. to 24°C., and it is believed that the actual range is somewhat greater.

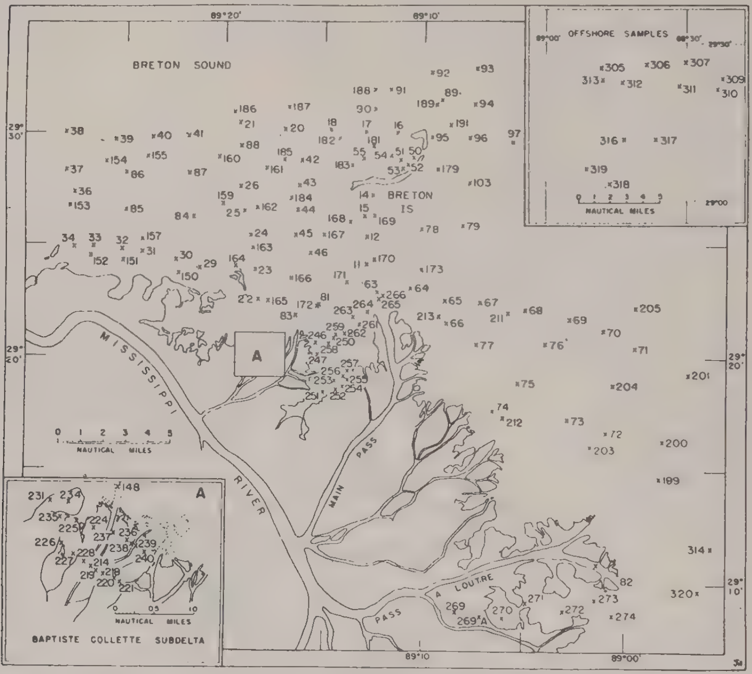

89°20'
89°10'
BRETON SOUND
BRETON IS
29° 30'
29° 20'
29° 10'
MISSISSIPPI RIVER
MAIN PASS
A LOUTRE PASS
A
0 1 2 3 4 5 NAUTICAL MILES
OFFSHORE SAMPLES
89°00'
88°30'
29°30'
29°00
0 1 2 3 4 5 NAUTICAL MILES
BAPTISTE COLLETTE SUBDELTA
0 0.5 1.0 NAUTICAL MILES
89°10
89°00'

FIG. 5.—Locations of stations.

One of the principal features of the physical oceanography of this area is the great variation which occurs from time to time and place to place. These variations, indicated principally by salinity, seem to be caused by the tides, local winds, and variations in runoff. Such variability in water features probably is characteristic of this delta-front environment.

Distribution of the sediments, in terms of sand, silt, and clay ratios is shown in Figure 4.

One hundred and seventy-four samples were collected for study of the Foraminifera. These stations are mostly in the area close inshore and extend 15–20 miles out from the coast. Two traverses of samples were collected from the marsh of Baptiste Collette Subdelta. Locations of the stations are given on Figure 5.

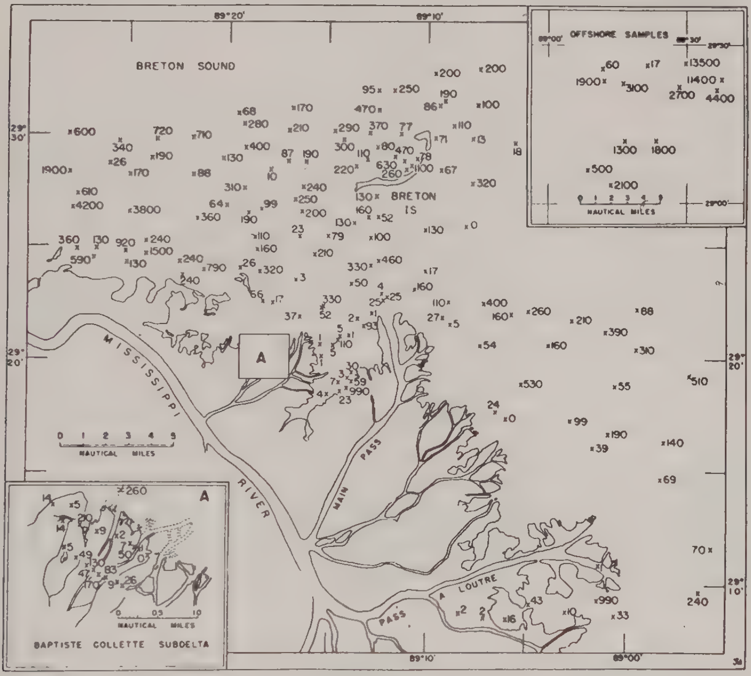

89°20'
89°10'
89°00'
29°30'
29°20'
29°10'
29°00'
BRETON SOUND
OFFSHORE SAMPLES
BRETON IS
MISSISSIPPI RIVER
MAIN PASS
A LOUTRE PASS
A
0 1 2 3 4 5 NAUTICAL MILES
BAPTISTE COLLETTE SUBDELTA
0 0.5 1.0 NAUTICAL MILES

FIG. 6.—Total populations in fraction larger than 0.149 mm.

METHOD OF STUDY

The samples were collected with a small coring tube (Phleger, 1951, p. 3) which obtains a surface sample $1\frac{3}{8}$ inch in diameter. A thickness of 1 cm. of surface material was taken from the top of each core and preserved in a neutral mixture of formalin and sea water; thus, approximately 10 ml. of wet sediment is contained in each sample.

In the laboratory each sample was washed over a brass sieve having nominal openings of 0.074 mm. The wet sample was treated with a solution of rose bengal which selectively stains the cytoplasm a bright red, a staining technique to detect living specimens described by Walton (1952). The entire sample was examined in a wet condition for the presence of Foraminifera containing cytoplasm (protoplasm). The presence of protoplasm in the foraminiferal test was taken as an indication that a specimen was alive at the time or shortly before collection on the basis that decomposition of protoplasm in the sea is very rapid. The wet samples were separated by a brass screen having nominal openings of 0.149 mm. into a fraction greater than 0.149 mm. and one smaller than 0.149 mm. and larger than 0.074 mm. The purpose of this was two-fold: to facilitate identifications, and to suggest size distribution of the living population. Many of the specimens smaller than 0.149 mm. are young forms which can not be identified specifically, and this procedure is an aid in their separation.

Table I. Distribution of Foraminifera in Per Cent of Total Population of Fine Fraction from Stations 11–54

STATION	11	12	14	15	16	17	18	20	21	22	23	24	25	26	29	30	31	32	33	34	36	37	38	39	40	41	42	43	44	45	46	50	51	52	53	54
TOTAL POPULATION <0.149 mm. and >0.074 mm.	490	930	4	330	8	570	570	470	240	360	560	580	880	1400	740	540	3300	2400	690	1000	1000	820	620	85	180	1100	250	560	750	87	200	51	110	420	87	350
Ammoastuta inepta												.2			.2	.2	.1		.3		.2															
Ammobaculites sp.								1	.8		.2			.3			.5	.2	.3	.4			.7				.8							.5		.2
A. exiguus	.8					2		.2	.4																			.4	.1					.2		.6
A. (young)	10	1	14	27	37	24	36	22	17	23	25	13	9	14	34	19	8	12	34	21	14	5	23	11	20	13	76	17	10	3	14	2	15	18	9	20
Arenoparrella mexicana										.8	.2			.3	.3		.5	.2	.3	.4	.2	.5													1	
Bolivina lowmani	.2	1		2			.3			.3	.2	.2	3		.2	.2												.4			2					
B. striatula	.4	1	7			.2	.3	.2	2	.6	.4	.3	.3	.6	.4	1	2	.8		.6	2	4				.8		.7	.5		2	4		.2		.3
Buliminella bossendorfensis	.4					.4		.2		.3				.3					.6		.2							.4								
B. elegantissima	.4	.3	7			.4							1	.1			.1									1		.2	.4		.5					
Elphidium (young)	1	3	14	2		6	10	17	25	21	34	21	16	26	24	27	36	44	30	42	46	54	51	47	34	40	2	23	18	1	9	4	17	18	20	9
Epistominella vitrea		.3																																		
Eponides hannai	.4									.6																										
Goudryina exilis				2		.4		1		.3	.2				.2	.2	.2				.2							.2	.1				1			
Haplophragmoides subinvolutum												.7					.3	.2			.2															
Lagenidae	2																											.2							–	
Miliammina fusca						.4				.3		.3	.2		.2	1	2	2	3	1	.8	R						.2								
Miliolidae	6	28	23	24		4	14	5	6	9	11	9	26	8	13	19	10	3	4	4	2	.5		5	2	6		13	11	2	13		23	28	44	20
Nonionella atlantica										.3																										
N. opima	5	16		2			1	.4	1	2	2	13	21	2	4	5	.2							1		.8			1	1	26					.3
Palmerinella palmerae										1	.5						.1			R	.2				.2											
Proteonina sp. A		.3																																		
Quinqueloculina cultrata		.3						.6					.1				.4												.1		.5					
Reophax nana	.4			2		1	1	.2			.2	.2	.5	.3					.6			.5				1			.1		.5					
Rotalia (young)	64	49	28	38	63	61	37	51	48	40	26	41	22	48	22	24	40	37	27	30	33	35	25	36	42	37	20	45	59	93	32	90	44	35	25	48
Textularia sp.																		.1											.1					.2		
Trochammina inflata										.3		.2									.4							.2							1	
T. macrescens		.2														1	.2												.1		.5					
T. spp.			7												.3	2						.5														

Only the living population was identified from the samples in water solution at most stations. Samples having a relatively large dead population were dried to facilitate counting the total population. A complete census was made on samples containing less than approximately 300 specimens. In larger samples a specific fraction, consisting of at least 300 specimens, was counted, and from this, the total population was estimated.

The occurrences of species are listed on Tables I–XI. Live and total populations and coarse and fine fractions are listed separately; the frequencies in these subdivisions are calculated separately so that each totals 100 per cent. Geographic distributions of some of the most common species are listed in Figures 12–40. Similar charts have been prepared of living populations for all the species, and these

TABLE II. DISTRIBUTION OF FORAMINIFERA IN PER CENT OF TOTAL POPULATION OF COARSE FRACTION FROM STATIONS 11–54

STATION	11	12	14	15	16	17	18	20	21	22	23	24	25	26	29	30	31	32	33	34	36	37	38	39	40	41	42	43	44	45	46	50	51	52	53	54
TOTAL POPULATION >0.149 mm.	330	100	130	160	77	370	290	210	280	66	320	110	190	310	790	240	1500	920	130	360	610	1900	600	340	720	710	190	240	200	23	210	78	630	1100	260	470
Ammoastuta inepta																	.1				.2					.3										
Ammobaculites sp.									.4					1											.1	.5										.4
A. dilatatus																.4			.8		.3		2		2											
A. exiguus	.3					.5		.5									.1										.5									
A. salsus	4	1	14	19	14	29	57	27	10	18	60	16	32	43	71	31	17	24	29	9	6	3	12	4	7	10	83	18	20	4	23	9	11	31	18	36
Ammoscolaria pseudospiralis	2		2	7		.8		8	36			1		2							.2	3	.7	7	.3	1	5	.4			2					
Arenoparrella mexicana	.3						.3			2		3			.1		.5	.4		.3	.3										.5					.2
Bolivina lowmani						.3							.5																							
B. striatula		1											.5	.3			.3					.2			.1						.5					.2
Cibicidina strattoni	.3		2	.7																				.3	.1							1				
Elphidium gunteri	6	2	14	8	44	8	8	19	25	8	7	8	5	7	5	21	25	31	34	45	54	53	55	48	48	41	4	21	18	4	15	38	41	32	40	17
E. incertum mexicanum	.6		6	2	6			2																.3	.5				.5		3	3	.2			
E. matagordanum			.8											.3			.4	.4		.8		.1							.5			1	.2	.6	.4	
E. poeyanum	11		14	3		4	2	2		3					.6	.4	3	3	2	3	1	1	1	.3	.8	.8		.4	3		6		.2	.4	1	2
E. sp.																																	4	2	9	
Eponides hannai	.3																																			
Gaudryina exilis			.8			.3	.3	.5						.6			.2	.2	2		.3		.3	.3	.1	.3	.5	1			.5			.1		
Haplophragmoides subinvolutum																	.1	.1				.1		.3					.5						.4	
Miliammina fusca															.3		.1	.2		.3		.1												.1		1
Miliolidae	4		8				.3				1	1			.6	.4												.8			4					
Nonionella atlantica	.3									2											.2				.1											
N. opima	3	12									.6	10	15	.3	1	1	.1											.4	2		6					
Palmerinella palmerae																				.3		.1														
Proteonina atlantica			.8				.3														.2					.8										
Quinqueloculina compta				.7																																
Q. cultrata	.3	2		3			.7										.5					.1			.3	.8		.4							.4	
Q. cf. funafutiensis						.3																.1														
Q. rhodiensis			.8				.7			2				.6	.1											.8			.5				3	2	1	2
Q. sp.	1		5	9	1		.7	1	1			1					.1					.3				.8		.4	.5		5					
Rotalia beccarii var. A	9		26	9	33	15	9	22	16	50	16	7	4	14	9	13	22	17	12	18	22	25	22	36	34	29	6	16	7	57	18	44	40	22	25	25
R. beccarii var. B	48	55	3	27		39	19	19	7	10	12	50	21	24	10	26	23	21	17	21	13	12	6	2	6	11	.5	32	39	35	11	4		7	2	14
Saccammina sp.				1																			.7													.2
Triloculina sidebottomi	9	27		11	1	4	3	2	4	3	3	3	23	7	2	6	7	2	2	1	.5	.8		.3	.1	3		9	9		4		.5	2	2	4
Trochammina inflata	.3		2							2							.1				.5														.4	
T. macrescens																.4		.3	.8	.3			.1										.2			

TABLE III. DISTRIBUTION OF LIVING FORAMINIFERA IN PER CENT OF TOTAL LIVING POPULATIONS OF SIZE FRACTIONS INDICATED FROM STATIONS 11–54

STATION	11	12	14	15	16	17	18	20	21	22	23	24	25	26	29	30	31	32	33	34	36	37	38	39	40	41	42	43	44	45	46	50	51	52	53	54
LIVING POPULATION >0.149 mm.	16	28	6	30	3	15	22	4	25	17	36	22	52	31	44	26	49	23	1	5	3	8	3	7	26	24	10	14	5	17	23	10	51	312	26	72
Ammobaculites salsus				21	67	27	40	50	8	12	17	14	27	29	25	30	6	17		20					11	4	90	29			9	20	8	8		3
A. dilatatus																							33		15											
Ammoscalaria pseudospiralis	19			16				25	28			4										12		14				7			4					
Bolivina striatula		4															2								4						4					
B. lowmani													2																							
Elphidium gunteri				3		7			8	12	11				2	15	2	13		20	67	50		14	15	8		7				40	13	59	80	7
E. poeyanum															2		2																			
Miliammina fusca															4			9																		
Miliolidae											8				7	4																				
Nonionella opima	6	43									3	41	53	3	25	12									4			7	40		48					
Proteonina atlantica			17				5																			8										
Quinqueloculina sp.			50	10			5		4																						4					
Quinqueloculina cultrata	6	4		10			5										2								8	13										
Q. cf. funafutiensis						7																														
Q. rhodiensis							5																												4	
Rotalia beccarii var. A	12			3	33	13	9	25	16	30	39	4	4	42	16	19	56	30		20		38	33	72	31	41	10			59		20	75	24	8	25
Rotalia beccarii var. B	44	50		16		39	26		8	42	11	36	4	19	16	8	20	30	100	40	33		33		8	13		21	60	41	27	20		8	8	61
Triloculina sidebottomi	12			13		7	5		28	6	11		10	6	2	8	6								4	12		29					2	.3		4
Trochammina inflata			33														2																			
T. macrescens																4																				
LIVING POPULATION <0.149 mm. and >0.074 mm.	34	303	4	104	5	25	58	18	37	90	60	130	310	230	87	78	112	85	10	18	18	17	8	2	32	34	16	11	11	75	126	44	48	112	3	71
Ammobaculites (young)	3	.3		14		8	14	21	3	8	18	7	6	2	25	23	16	13	10	17	6				12	6	25	36	9		3		12	16		
Bolivina spp.																											6									
B. lowmani	3	3		8							2		7			1															3					
B. striatula		1	25			4		6	8		2	8	.6	2	3	3	4	5		11	38	41				3			9		4	5		1		
Buliminella bassendorfensis										1				.4					10																	
B elegantissima													3	1			1														.8					
Elphidium (young)	9	.7				4			5	26	27	3	4	5	5	9	12	5	40	38	22	29	50		12	14	12		9	1	2		15	20	67	1
Gaudryina exilis				8													1											9					2			
Haplophragmoides subinvolutum												.8																								
Miliammina fusca										1						1	1	4	10																	
Miliolidae	12	3		31		24	20	11	16	9	15	2	3	6	8	17	8	4	10	6	11			100	12	15		9	27		4		17	6		14
Nonionella opima	44	47		8			5		3	9	12	53	58	8	25	36	3									3			27	1	42					1
Palmerinella palmerae										1																										
Proteonina sp. A		1																																		
Quinqueloculina cultrata		.7						6																							.8					
Reophax nana								6				.8	.6	.4								6									.8					
Rotalia (young)	27	43	50	31	100	56	61	50	62	43	24	32	17	75	31	10	54	69	20	28	23	18	50		64	59	57	45	18	98	40	95	54	56	33	83
Trochammina spp			25																			6														

Table IV. Distribution of Foraminifera in Per Cent of Total Population of Fine Fraction from Stations 55–103

STATION	55	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	81	82	83	84	85	86	87	88	89	90	91	92	93	94	95	96	97	103
TOTAL POPULATION <0.149 mm. and >0.074 mm.	48	16	330	270	26	520	2000	730	3000	2800	630	350	23	1100	630	130	230	1	700	4	96	250	500	140	24	190	480	210	850	740	360	280	89	19	18	740
Ammoastuta inepta					4																											.4				
Ammobaculites sp.																							.8							.1	.3	.4				
A. exiguus														.6								2		4						.1	.6					1
A. (young)	17	19	34	20	31	12	7		.7		.5	6	43	21	3	41	9	100	20	50	10	12	25	36	21	6	11	7	20	14	57	22	25	16		34
Arenoparrella mexicana													4	.2										2												
Bigenerina irregularis							.4		.1																											
Bolivina lowmani			2	1		2	10	5	3	1	4	6		4	4		1		.1	25							.8	1	.7	.7	.6	1				2
B. striatula							.8	1	.8	.6		.6		.7	.8	.8	1					2	.8		25	1	.8	1	.5	1	.3					.5
Buliminella bassendorfensis		12	2	.4			1	8	14	20	7	.6		.6	.5												.8			.3	.6	.4				.5
B. elegantissima			.3					.5	.1	.6				.3			.4						.8			1	.8		.5	.3		1				1
Cibicidina strattoni							.4	.3	.1					.3																						
Elphidium (young)		12	14	18	4	2	3	3	2	4	3	7	9	12	6	13	3		25		9	10	33	27	17	7	16	9	15	11	6	8	12	32		6
Epistominella vitrea							.4		4	9	26	1			.3																					
Eponides hannai																																				.2
Gaudryina exilis			.3											.1		.8	2						.8								.6	.7	1			
Lagenidae									.3	.6																										
Miliammina fusca					8							.3												.7												
Miliolidae		12	21	25	15	28	3	14	5	6	2	4	9	11	4	9	11		23			65	7	4	25	60	13	21	4	16	5	2	13	20		4
Nonionella atlantica			1	.7						.1																										
N. opima		12	4	2		5	34	22	48	38	33	46	9	12	31	4	.4		4			.4					.8		.2	.4	2	3				.5
Nouria polymorphinoides								.1		.4	.3																				.6					
Palmerinella palmerae										.3			4						9		13	.4														
Proteonina sp. A											6	.6			.8												.8			.1	1	2				.2
Quinqueloculina cultrata			.3	.7				.3									.4						2				2									
Reophax nana			1	.7			.4				.3			.4	2												.8			.3	.8	3				2
Rotalia (young)	83	32	19	31	38	51	39	46	17	16	8	27	22	36	49	31	72		19	25	68	8	28	27	12	25	53	61	59	55	24	56	49	32	100	48
Textularia sp.									3		10	.6							.4																	.2
Trochammina (young)																																				.2
Virgulina pontoni			.3					.3	.7	3	.2			.3																						.2

Table V. Distribution of Foraminifera in Per Cent of Total Population of Coarse Fraction from Stations 55–103

STATION	55	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	81	82	83	84	85	86	87	88	89	90	91	92	93	94	95	96	97	103
TOTAL POPULATION >0.149 mm.	110	4	160	110	5	400	260	210	390	310	190	99	24	530	160	54	130	0	330	1	37	360	3800	170	88	400	190	470	250	200	200	100	71	13	18	320
Ammoastuta inepta																								.6												
Ammobaculites sp.																							2													
A. dilatatus																						.3	2													
A. exiguus																						2		.6												
A. salsus	4	25	42	29	40	9	5		3			8	55	15	4	64	21		63	100	16	6	11	8	5	5	2	2	9	23	79	45	21	15	11	39
Ammoscalaria pseudospiralis	4			2		.3			.8	.7				.4								8	3		61	20	28	7	36	15	1		3	15		
Arenoparrella mexicana																								4							.5					
Bigenerina irregularis									.5	.7																										
Bolivina striatula							.4															1	.2		2	.5										.3
Buliminella bassendorfensis									.3	3	2																									
Cibicidina strattoni						1	.4	.5	2					.8	.6									2				.2								
Elphidium gunteri	48		.6	15	20	5	5	11	14	9	12	17	4	6	5	6	3		5			22	45	40	14	11	15	31	20	6	3	6	37	15	50	8
E. incertum mexicanum						2								.6	1	2	.8					.3		3		.3	3	.4	1			1		8		.6
E. matagordanum														.2										2								2				.6
E. poeyanum			7	12		13	2	3	.8					13		6	2					.3	.6	7			2	1	7	13	.5	3	6		6	3
Epistominella vitrea							.4		1	3	32	1																								
Eponides hannai							.4	1																												
Gaudryina exilis				1										.6			5					.3	2			.5				.5	1				6	1
Haplophragmoides subinvolutum												2												1												
Miliammina fusca																							2													
Miliolidae								1			.5			4			1											4								.3
Nonionella atlantica			1	1		.5		5	2	4				1	1									.6				.2			.5	3				.3
N. opima		25	6	4		3	15	13	39	42	45	47	33	19	22	6			13								.5			2	6	5	3			.3
Nouria polymorphinoides				1				1		3	.5																									
Palmerinella palmerae																					3															
Proteonina atlantica									.3	.7																				.5						
P. sp. A							.4				.1				.6															.5		1				
Quinqueloculina compta							.4	3	.8																											
Q. cultrata						.5				.3		2		.2	.6		.8					.3	2		1		1			.5	.5					
Q. cf. funafutiensis						.3																														
Q. rhodiensis												1																								
Q. sp.	1		.6	1		5	3		.5					2	1	2	5					2				3	28	18	2	4			11	8	6	3
Rotalia beccarii var. A	39	25	1	8		5	4	2	1				4	9	1	2	13		5		81	12	26	24	5	9	13	20	18	16	2	7	15	15	21	11
R. beccarii var. B	2	25	21	18	40	47	58	54	29	23	4	17		19	56	10	45		10			6	9	4		15	3	8	7	15	5	24	4	23		31
Saccammina sp. *																						1			1											
Triloculina sidebottomi	1		20	8		7	5	3	3	1	3	6	4	7	7	2	4		4			38	1	1	11	34	5	8		4						3
Trochammina inflata									.3															1												
T. macrescens																														.5						
Virgulina pontoni								.5	.3	.3				.4	.6																	1				

are on file at the Marine Foraminifera Laboratory. The environmental distributions of the important species are generalized in Figure 10.

The present samples were collected during two field seasons, November-December, 1951, and April-June, 1952. The faunas from samples collected during these two seasons are treated here as a unit. The reasons for this are that each season's sampling was done in a somewhat different area, and it seems desirable to obtain a general idea of the standing crop for the area as a whole. The living populations, therefore, do not represent the standing crop of Foraminifera during a single season. The distributions are so consistent, however, that it is believed that living distributions shown are a fair generalization for the area covered. It is hoped that seasonal sampling over a long period of time for the living population can be done at some future date.

The eleven offshore samples contain faunas which are different in many respects from the rest of the area. These faunas are not reported in detail at this time.

BIOFACIES

MARSH FACIES

Eighteen samples were collected from the marsh of Baptiste Collette Subdelta. These samples have a distinctive fauna dominated by the following.

Leptodermella variabilis Parker
Miliammina fusca (H. B. Brady)
Trochammina macrescens H. B. Brady

The following species appear also to be confined to the marsh, but occur in lower frequencies.

Ammoastuta inepta (Cushman and McCulloch)
Arenoparrella mexicana (Kornfeld)
Miliammina sp.
Proteonina lagenaria (Berthelin)

Ammobaculites, especially *A. salsus* Cushman and Bronnimann, also occurs in significant frequencies in the marsh samples, but these forms are especially characteristic of Breton Sound. *Trochammina inflata* (Montagu) has been found only in Breton Sound but it is believed to be a marsh species, based on data from other areas. *Haplophragmoides subinvolutum* Cushman and McCulloch is believed to be a marsh species but also occurs in the bays and Breton Sound; it is present at only a few stations in all three environments.

BRETON SOUND FACIES

The geographic boundary for this facies is taken as a line extending south from the southwestern end of Breton Island to Main Pass. This boundary is arbitrary but it appears to show the facies relationships. Foraminifera which are characteristic of this facies are the various species of *Ammobaculites*, *Ammoscalaria pseudospiralis* (Williamson), and *Gaudryina exilis* Cushman and Bronnimann.

Table VI. Distribution of Living Foraminifera in Per Cent of Total Living Populations of Size Fractions Indicated from Stations 55–103

STATION	55	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	81	82	83	84	85	86	87	88	89	90	91	92	93	94	95	96	97	103
LIVING POPULATION >0.149 mm.	25	1	8	9	0	20	28	22	40	26	14	40	10	103	11	6	44	0	37	0	0	59	80	21	19	15	4	41	16	4	20	6	2	1	2	36
Ammobaculites salsus			75	45		5			3			2	10	5		50			5			2	30			7		10	25		20	17	100		50	20
Ammoscalaria pseudospiralis	4								5					1								12	30		59	7	75	27	37	25						
Bigenerina irregularis									3																											
Bolivina striatula																						8			10	13										
Elphidium gunteri	40						4	4	7				10				2					25	10	90	5			12		25					50	3
E. poeyanum						10								1																						
Epistominella vitrea									5	4	43																									3
Gaudryina exilis				11																																
Nonionella atlantica								9																												
N. opima		100		11		45	45	15	45	57	29	95	80	85	73				84												55	32				
Nouria sp.							4																													
N. polymorphinoides				11				15		27	7																									
Proteonina sp. A							4								9																	17				
Quinqueloculina sp.																						7								25				100		6
Q. compta								4																												
Q. cultrata														1			2								5											
Rotalia beccarii var. A	40						4	4								17	12					13			10		25	17	19	25	5					14
R. beccarii var. B	8		25	22		40	35	51	32	8	21	2		3	18	33	80		8			5	30			27		7	19		10	17				54
Trilocutina sidebottomi	4						4							4			4		3			29		10	10	46		27								
Virgulina pontoni										4																										
LIVING POPULATION <0.149 mm. and >0.074 mm.	36	2	14	23	3	84	880	151	112	546	185	154	4	288	202	18	89	0	53	0	5	40	20	3	15	12	44	51	21	33	31	17	10	4	15	130
Ammobaculites (young)			29	17		5	1		.7		.5		50	9	.5	51			17			5		33		17			24	3	3	6	20			8
Bolivina lowmani						14	13	3	3		12	12		8	7		2		2								9	2	14	6	3	18				7
B. striatula							1	.7				1		1	1	5	2					13			40			2	5	9						.8
Buliminella bassendorfensis			14				2	3	7	1	5															17										
B. elegantissima																							20							3						.8
Elphidium (young)				9				.7	.4	.2	.5	.6		3	.5				37			23	40	33	20		9		5				10	25		2
Epistominella vitrea										1	6																									
Gaudryina exilis														.3		5	1															6	10			
Miliolidae			14	30	33	5		1	1		.5	.6		7	2	5	10		6			45		33	20	33	27	14	9	18	3		10			5
Nonionella opima		50	7	4		28	75	61	85	94	55	83	50	47	76	5	1		9			2					9		5		26	12				2
Nouria polymorphinoides								.7		2																					6					
Palmerinella palmerae																			8			2														
Proteonina sp. A											14	1			1												9				10	6				
Quinqueloculina cultrata																	1						20													
Reophax nana				4										1																3						4
Rotalia (young)	100	50	36	36	67	48	8	30	3	2	7	1		23	12	29	83		21		100	10	20		20	33	37	82	38	58	49	52	50	75	100	68
Trochammina spp.																																				.8

Table VII. Distribution of Foraminifera in Per Cent of Total Population of fine Fraction from Stations 148–213

STATION	148	150	151	152	153	154	155	157	159	160	161	162	163	164	165	166	167	168	169	170	171	172	173	179	181	182	183	184	185	186	187	188	189	191	199	200	203	204	205	211	212	213
TOTAL POPULATION <0.149 mm. and >0.074 mm.	430	390	190	1000	2600	11	50	620	78	98	43	310	780	43	44	12	81	170	58	97	99	69	11	89	24	120	55	730	700	150	58	170	120	110	230	860	120	350	620	820	10	74
Ammoastuta inepta			.5										.5																													
Ammobaculites sp										1																2			.6													
A. exiguus			1					.3	1																	2				.7												
A. (young)		16	50	36	4	45	38	41	32	86	73	6	11	25	25	42	16	16	48	31	8	97	91	47	[illegible]	89	34	9	4	38	67	34	21	37	2		6	.3	1	.5		35
Arenoparrella mexicana		1	4					.3			2	.3	2													.8																
Bigenerina irregularis																					1																					
Bolivina lowmani												1					2		2	10	3												2					1	.3	3	30	8
B striatula	1	.3			.1		2		1			.3	2				4	2									6	.1	1	2	2							.3				
Buliminella bassendorfensis	1																				3							1							2	15	2	10	9	2		
B elegantissima		.3										.6	.5				2											1	1			1	.8	1					.3			
Cibicidina strattoni	4	.5																																								
Elphidium (young)	51	39	5	40	61	10	26	21	18	1		15	31	28	57		16	35	15	12	47		9	6			9	11	37	29	15	23	31	19	.4	.6	36	1	4	6	20	16
Epistominella vitrea																																			.9	29	3	7		2		1
Gaudryina exilis	1						2	.6																						.7												
Leptodermella variabilis																																									30	
Miliammina fusca			2					.6																																		
Miliolidae			2	2	.1		2	6	9			13	7	2	7		12	16	5	8	16			8				38		2		2		5	11	1	3	3	1	5		7
Nonionella atlantica	5																																					.3				
N. opima	4	.5						.3				1	.5				11	2		3	10			2				.5					.4	2	56	22	23	36	29	48	10	18
Nouria polymorphinoides																																			1	.2				.5		
Proteonina sp. A																																	2		.4	1		.6	.1			
Quinqueloculina cultrata																																2			.4				.1			
Reophax nana			.5								2	1																.5											.1			
Rotalia (young)	30	42	35	22	35	45	30	29	39	12	16	60	40	43	11	25	37	29	26	36	12	3		37		6	34	39	56	28	14	40	39	36	12	.7	13	30	45	31	10	14
Textularia sp																																			.5	29		9	6			
Trochammina sp																											17												.5			
T macrescens											2	.6	1																							.2				1		
T. (young)								.3			5	.3	3	2		33																										
Virgulina pontoni	3																																					.6	.3			

Various species of *Elphidium* and "*Rotalia*" *beccarii* (Linné) vars., are very abundant in the sound but are equally abundant in the open gulf. *Elphidium incertum mexicanum* Kornfeld appears to be largely confined to this facies, occurring only in low frequencies in the open gulf. *E. matagordanum* (Kornfeld), while rare, is restricted to Breton Sound. *Quinqueloculina cultrata* (H. B. Brady) and *Triloculina sidebottomi* (Martinotti) are most abundant in the sound. *Quinqueloculina rhodiensis* Parker is essentially restricted to Breton Sound, but is rare. Other Miliolidae are abundant in the sound but also are abundant in the open gulf. Several of the open-gulf species occur in the sound facies, but mostly in the wide inlet between Breton Island and Main Pass.

Bolivina striatula Cushman appears to be most abundant in the sound.

Most of the samples in the present suite containing *Buliminella elegantissima* (d'Orbigny) are from Breton Sound, but this species is confined to the open gulf in other Gulf of Mexico nearshore areas studied.

OPEN-GULF FACIES

The open-gulf facies, seaward from Breton Island and Main Pass, is characterized by the following species which are essentially restricted to this facies.

Bigenerina irregularis Phleger and Parker
Bolivina lowmani Phleger and Parker
Buccella hannai (Phleger and Parker)
Buliminella cf. *bassendorfensis* Cushman and Parker
Cibicidina strattoni (Applin)
Epistominella vitrea Parker
Nonionella atlantica Cushman
N. opima Cushman
Nouria polymorphinoides Heron-Allen and Earland
Proteonina sp. A
Quinqueloculina cf. *compta* Cushman
"*Rotalia*" *rolshauseni* Cushman and Bermudez
Virgulina pontoni Cushman

The following species occur in abundance in the open gulf but also are abundant in Breton Sound.

Elphidium gunteri Cole
E. spp.
Miliolidae
"*Rotalia*" *beccarii* (Linné) variants

Ammobaculites occurs at numerous open-gulf stations, especially the inner part of the area, although the most abundant occurrences are in the sound.

OFFSHORE "SUBFACIES"

A few species are either restricted or more abundant in the offshore part of the open-gulf area covered by the present samples. Most of these "offshore" stations lie generally east of 89° W. Long. and are deeper than 10 fathoms, with most stations at a depth of 20 fathoms or more. The following species seem to be characteristic of this subfacies.

Bigenerina irregularis Phleger and Parker
Epistominella vitrea Parker

TABLE VIII. DISTRIBUTION OF FORAMINIFERA IN PER CENT OF TOTAL POPULATION OF COARSE FRACTION FROM STATIONS 148–213

STATION	148	150	151	152	153	154	155	157	159	160	161	162	163	164	165	166	167	168	169	170	171	172	173	179	181	182	183	184	185	186	187	188	189	191	199	200	203	204	205	211	212	213
TOTAL POPULATION >0.149 mm.	260	240	130	590	4200	26	190	240	64	130	10	99	160	26	17	3	79	130	52	460	50	52	17	67	80	300	220	250	87	68	170	95	86	110	69	140	39	55	88	160	0	27
Ammoastuta inepta					.4			4																		.3																
Ammobaculites sp.				.2					2	.8																1																
A. dilatatus					.8		.5	2		2																																
A. exiguus						8	.5													1						1	.5															
A. salsus		29	84	23	.4	8	19	53	37	70	60	32	33	72	70	67	5	11	19	14	70	92	100	71	71	97	26	5	6	27	21	9	13	33	7		3		3	2		74
Ammoscalaria pseudospiralis	3	.4			.4	42	8	.4	5	23	30						4		4	8					28		23			27	46	68	60	8								
Arenoparrella mexicana			2		.4													.8						1																		
Bolivina lowmani												1								.6																				2		
B. striatula																		.8		.4																						
Buliminella bassendorfensis																				.4															1					.6		
B. elegantissima																												.4	1													
Cibicidinia strattoni	7	.4																		2							.5															
Elphidium discoidale	40	.4																																								
E. gunteri	16	20	3	40	51		38	11	16	.8		6	5	8	6		21	23	2	11	16	2		3	1		7	15	34	28	8	9	13	9		1	65	11	16	7		4
E. incertum mexicanum	2				.4												5	2		4																				1		
E. matagordanum				.2				.8									1	.8		.2	2													1								
E. poeyanum					2		.5	.4					.6	4			5	.8		6				3			2	.4			1	1		2						5		7
Epistominella vitrea																																			12	45		7		.6		
Goudryina exilis	.8	.4	.8					.8	2	2								.8		2										3										.6		
Miliammina fusca				.3																																						
Miliolidae							.5						.6							1											.6	1										
Nonionella atlantica	3																										.5									1				1		
N. opima	.8								2			8	3							2	2			3				2	1						71	42	10	33	38	25		
Nouria polymorphinoides																																			1	3	3			.6		
Quinqueloculina sp.									3								3	6		5				3			3	.4				3	5	5		1				2		
Q. compta																				.6																		2				
Q. cultrata																																		3	3					.6		
Q. rhodiensis																		2		.2							.5	1														
Reophax gracilis																																						2				
R. nana																				.2						.3																
Robulus																																				.7						
Rotalia beccarii var. A	22	43	9	22	28		28	20	22		10	11	8		24		20	13	29	15							9	6	23	9	20	5	3	18				5	7	9		
R. beccarii var. B	3	6	.8	13	14		4	3	8			32	29	12			26	23	4	23	4			3		.3	5	44	34	6	3	2	3	4	1	1	14	38	33	26		
Saccammina sp.						42	.5												4	.2													2	4								
Triloculina sidebottomi			.8	.9	1			4	3			10	20	4			10	15	38	3	6			13			3	26					1	13	4	1	5			16		15
Trochammina sp.																											20					2										
T. inflata																33																										
T. macrescens					.8					.8			.6							.2									1											.6		

TABLE IX. DISTRIBUTION OF LIVING FORAMINIFERA IN PER CENT OF TOTAL LIVING POPULATIONS OF SIZE FRACTIONS INDICATED FROM STATIONS 148–213

STATION	148	150	151	152	153	154	155	157	159	160	161	162	163	164	165	166	167	168	169	170	171	172	173	179	181	182	183	184	185	186	187	188	189	191	199	200	203	204	205	211	212	213
LIVING POPULATION > 0.149 mm.	5	31	19	25	14	11	40	13	5	25	3	31	43	3	13	1	17	37	13	20	41	18	16	48	12	37	114	35	15	15	42	19	26	45	12	16	6	2	3	55	0	23
Ammobaculites sp.										4																																
A. dilatatus										4																																
A. exiguus																										3																
A. salsus		55	63	28		9	25	50	20	72		55	77	67	92	100	6	22	54	25	81	100	100	90	100	91	27	3	7	20	35	5	30	52	25					2		79
Ammoscalaria sp.										4							18																									
A. pseudospiralis						9	8			16	67									10							18			60	50	65	50	4								
Bolivina lowmani												3								10																				5		
B. striatula																		3																								
Buliminella bassendorfensis																				5																				2		
B. elegantissima																												3	7													
Cibicidina strattoni	20																																									
Elphidium gunteri		3	21	36	39		34	23	20			3			8		12	16		10	10			2				9	46	13			4	7			33		33	2		4
E. matagordanum								8																																		
E. poeyanum					7																											5										
Epistominella vitrea																																			8	50				2		
Goudryina exilis																																								2		
Miliammina fusca				4																																						
Nonionella opima												3								10	2			2											67	44	50		33	47		
Nouria sp.																																							33			
N. polymorphinoides																																								2		
Proteonina sp. A																																				6						
Quinqueloculina spp.																		8						2			4	9				5		4						2		
Reophax spp.																										3												50				
Rotalia beccarii var. A	60	32	11	32	50		25	46	40		33	10	7				23	5	8	15							3	11	20		10		4	2						7		
R. beccarii var. B	20	10			14		8	8	20			20	14	33			6	22	8	10						3	7	23	20	7	5	5					17	50		7		
Saccammina sp.						82													15														8	4								
Triloculina sidebottomi			5									6	2				35	24	15	5	7			4			3	42					4	27						20		17
Trochammina sp.																											38					10										
LIVING POPULATION <0.149 mm. and >0.074 mm.	4	56	38	64	5	6	12	102	10	29	8	156	144	4	26	6	42	90	35	14	60	14	8	48	7	23	27	46	40	24	12	19	41	20	29	115	38	29	67	444	4	33
Ammobaculites (young)		18	24	69			8	12		66	25	6	22	25	27	67	17	18	34	7	7	93	88	82	100	70	22	22	10	51	25	43	24	25			8	3				42
Bolivina lowmani												2					2		3	29	5												5					3	3	6	75	14
B. striatula		2			40		8		10				3				7	3									7	2	10	8	8							3				
Buliminella bassendorfensis																					5							4							7	30		14	23	3		
B. elegantissima		2										.6	3				5											9	10			10	2	5								
Cibicidina strattoni	25																																									
Elphidium (young)	25	30	16	6	20	17	25	29				12	25	50	58		19	43	23	14	44		12				7	13	30	12	8	21	27	20		1	18			2		14
Epistominella vitrea																																			17	33	5	14		4		
Miliolidae					20				10			1	6				12	20	9	29	22			10				9		12		5		25			3	3	1	2		2
Nonionella opima												.6					21	3		14	17			4									10	10	53	21	66	39	42	77	25	23
Nouria polymorphinoides																																			3					1		
Proteonina sp. A																																			3	4		3				
Reophax nana											12	1																														
Rotalia (young)	50	38	60	25	20	83	59	59	80	34	63	75	41	25	15	33	17	13	28	7		7		4		30	42	41	40	17	59	21	32	15	14			14	23	5		5
Saccammina sp.																			3																				7			
Textularia sp.																																			3	10		3				
Trochammina sp.																											22															

Nouria polymorphinoides Heron-Allen and Earland
Proteonina atlantica Cushman
"Rotalia" rolshauseni Cushman and Bermudez

Cibicidina strattoni (Applin) is more abundant at these offshore stations than elsewhere. There is a marked lower frequency of *Elphidium* and of *"Rotalia" beccarii* (Linné) variants in this subfacies than in the shoaler open-gulf assemblages.

FAUNAL TRANSITION AREAS

There are two areas of faunal mixing at boundary zones between facies. The principal one of these is in the wide inlet between Breton Island and Main Pass on the Mississippi Delta. Here there is general mixing of many open-gulf and sound species over a distance of approximately 10–15 miles. Typical sound facies species which occur in the inner part of the open gulf, seaward from the pass, are the following.

Ammobaculites salsus Cushman and Bronnimann
Ammoscalaria pseudospiralis (Williamson)
Elphidium incertum mexicanum Kornfeld
Gaudryina exilis Cushman and Bronnimann
Quinqueloculina cultrata (H. B. Brady)
Triloculina sidebottomi (Martinotti)

Typical open-gulf species which occur in the sound for a few miles landward from this pass are the following.

Bolivina lowmani Phleger and Parker
Cibicidina strattoni (Applin)
Nonionella opima Cushman

Also, in this mixed or transition zone there is a more abundant fauna of Miliolidae than elsewhere in the area.

Another area of mixing occurs in the bays and in areas of Breton Sound which are near the marsh. Various species of *Ammobaculites*, particularly *A. salsus* Cushman and Bronnimann, are almost as abundant in the bays as in the sound. *Gaudryina exilis* Cushman and Bronnimann, *Quinqueloculina cultrata* (H. B. Brady), and *Triloculina sidebottomi* (Martinotti), however, are not recorded from the bays. *Elphidium* and *"Rotalia" beccarii* (Linné) variants are present in the bays in appreciable frequencies. *Elphidium delicatulum* Bermudez appears to be restricted to the bays, but it is rare. The marsh species also occur in the bays and in very nearshore areas in Breton Sound, especially *Leptodermella variabilis* Parker and *Miliammina fusca* (H. B. Brady).

It is possible that these two environments containing mixed assemblages should be considered subfacies.

LIVING AND TOTAL POPULATIONS

The distributions of the living populations may be obtained from Tables III, VI, IX, and XI, and in addition, several species are plotted geographically

TABLE X. DISTRIBUTION OF FORAMINIFERA IN PER CENT OF TOTAL POPULATION OF SIZE FRACTIONS INDICATED FROM STATIONS 214–274

STATION	214	218	219	220	221	224	225	226	227	228	231	234	235	236	237	238	239	240
TOTAL POPULATION >0.149 mm.	47	170	83	9	26	9	210	5	49	130	14	5	14	7	2	50	1	0
Ammoastuta inepta	64	1	79	22	19	11			32	39			36			76		
Ammobaculites salsus					4	22	50			5	36	40	7	14	50		100	
A. sp.		13							4	6								
Arenoparrella mexicana	2		2															
Elphidium delicatulum																		
E. gunteri							.5											
Haplophragmoides subinvolutum																		
Leptodermella variabilis		37	13	33	50									29				
Miliammina fusca		5					23	20	31	42	43	40	21			18		
M. sp.	4	1	4	11	23					2						6		
Palmerinella palmerae																		
Proteonina lagenaria		15																
Recurvoides sp.	13														50			
Rotalia beccarii var. A							15											
Rotalia beccarii var. B							.5											
Trochammina macrescens		11	2	22	4	67	11	80	43	6	21	20	36	57				
TOTAL POPULATION <0.149 mm. and >0.074 mm.	310	210	190	290	630	36	440	18	66	220	17	18	20	52	13	190	12	130
Ammoastuta inepta	11		5		.2				6	35			5		8	15		
Ammobaculites (young)	.7	1				20	32		30	16	18	6	15	2	15			
Arenoparrella mexicana	2									.5						9		
Buliminella bassendorfensis																		
Elphidium (young)							1											
Haplophragmoides subinvolutum	15															5		
Lagunculina vadescens				.3	.5												8	
Leptodermella variabilis		62	75	83	84		.2			2				82	47		68	88
Miliammina fusca	1	2		.3	2	33	16	83	52	37	70	66	35	4	15	2	8	.8
M. sp.	51	1	9	.7	3					1						20	8	
Palmerinella palmerae																		
Proteonina lagenaria		5		1	2													6
R sp. A																		
Recurvoides sp.	3																	
Rotalia (young)						30	46				6						8	
Trochammina macrescens		5	4	2		36	5	11	12	8	6	28	30	6		9		
T. (young)	10												15		15	40		
Urnulina		24	7	13	8			6						6				5

STATION	246	247	250	251	252	253	254	255	256	257	258	259	261	262	263	264	265	266	269	269A	270	271	272	273	274
TOTAL POPULATION >0.149 mm.	1	1	110	4	23	7	990	59	3	30	5	5	93	1	2	1	25	25	2	2	16	43	10	990	33
Ammoastuta inepta						14							1												
Ammobaculites salsus	100	100	98	75			96	93	33	63	20	80	5		50	100	50	4			44	89	80	60	94
A. sp.							.1																		
Arenoparrella mexicana							.1		33				3												
Elphidium delicatulum					96	72											50	4			56			31	3
E. gunteri								2		7	20		6					8				2			
Haplophragmoides subinvolutum				25		14																			
Leptodermella variabilis					4										50				50	100		9			
Miliammina fusca							4	3		3				100									20	9	
M. sp.																									
Palmerinella palmerae			1							10			4												
Proteonina lagenaria								2																	
Recurvoides sp.																									
Rotalia beccarii var. A			1						33	17		20	13					80	50						3
Rotalia beccarii var. B											60		42					4							
Trochammina macrescens																									
TOTAL POPULATION <0.149 mm. and >0.074 mm.	4	2	250	8	47	57	1900	20	17	130	31	27	190	16	6	2	9	29	10	10	36	68	140	1600	18
Ammoastuta inepta						2																			
Ammobaculites (young)	75		95	88		41	97	75	64	41		37	4	6	68	100	67	17	20		42	70	61	63	94
Arenoparrella mexicana						2																			
Buliminella bassendorfensis		50							6																
Elphidium (young)					94	5			6	8	26		8		17			14			49		17	22	
Haplophragmoides subinvolutum																						4			
Lagunculina vadescens																									
Leptodermella variabilis				12	4	14				2		15	1	13			22		60	90	3	19	1		
Miliammina fusca			.4			10	2			9			2								3		21	15	
M. sp.																									
Palmerinella palmerae										14		7	9												
Proteonina lagenaria												4	1									1			
R sp. A											61														
Recurvoides sp.																									
Rotalia (young)	25	50	5			2		25	12	25	13	37	74	81	17		11	69	10	10	3	3		.1	6
Trochammina macrescens																									
T. (young)																									
Urnulina						2	.4		6	.8									10			3			

TABLE XI. DISTRIBUTION OF LIVING FORAMINIFERA IN PER CENT OF TOTAL LIVING POPULATIONS OF SIZE FRACTIONS INDICATED FROM STATIONS 214–274

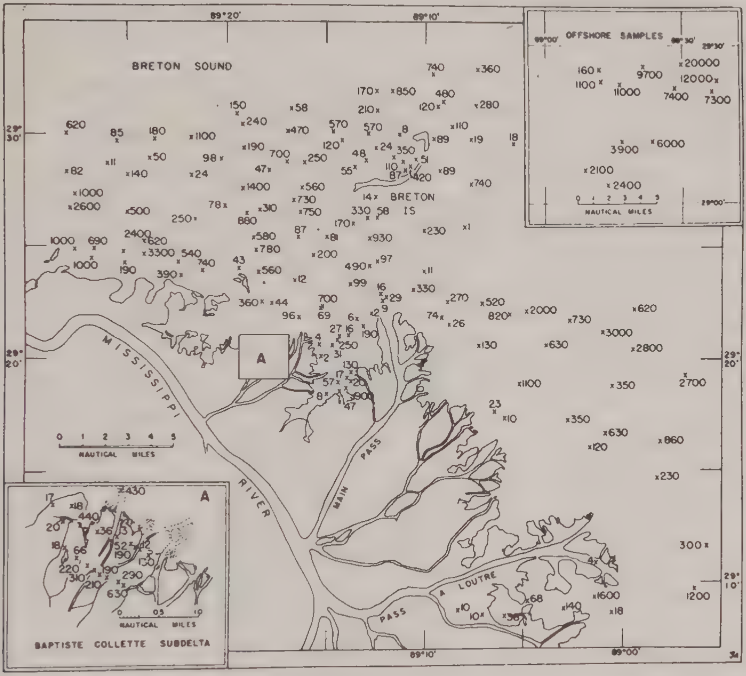
STATION	214	218	219	220	221	224	225	226	227	228	231	234	235	236	237	238	239	240
LIVING POPULATION >0.149 mm.	6	7	39	1	3	8	149	1	4	33	2	0	9	1	0	11	0	0
Ammoastuta inepta	100		100		100	12			50	67			56			91		
Ammobaculites salsus						12	52			9								
A. sp.		14																
Elphidium delicatulum																		
E. gunteri							.7											
Leptodermella variabilis		58		100														
Miliammina fusca							17			18	100		22			9		
Proteonina lagenaria																		
Rotalia beccarii var. A							19											
R. beccarii var. B							.7											
R. beccarii var. C							.7											
Trochammina macrescens						76	9	100	50	6			22	100				
Urnulina		28																
LIVING POPULATION <0.149 mm. and >0.074 mm.	141	11	14	5	15	20	364	1	2	89	9	0	9	0	1	85	3	6
Ammoastuta inepta	11		50						100	66			11			12		
Ammobaculites (young)						15	27			20	11		11					
Arenoparrella mexicana	.7															11		
Elphidium (young)							1											
Haplophragmoides subinvolutum	9															4		
Leptodermella variabilis		82	14	60	54					1							33	83
Miliammina fusca					13	30	15	100		9	78		45		100	1		
M sp.	67		36		20											16	33	
Palmerinella palmerae																		
Proteonina lagenaria				20	13													17
P sp. A																		
Recurvoides sp.	1																	
Rotalia (young)						20	55				11						33	
Trochammina macrescens						35	2			4			11			4		
T. (young)	9												22			52		
Urnulina		18		20														

STATION	246	247	250	251	252	253	254	255	256	257	258	259	261	262	263	264	265	266	269	269A	270	271	272	273	274
LIVING POPULATION >0.149 mm.	0	0	5	0	22	5	62	1	0	1	5	4	43	0	0	0	0	1	0	0	9	6	2	195	4
Ammoastuta inepta																									
Ammobaculites salsus			100				94			100	20	75										100		12	50
A. sp.																									
Elphidium delicatulum					100	100															100			86	25
E. gunteri											20		9												
Leptodermella variabilis																									
Miliammina fusca							6																100	2	
Proteonina lagenaria								100																	
Rotalia beccarii var. A												25	16					100							25
R. beccarii var. B											60		66												
R. beccarii var. C													9												
Trochammina macrescens																									
Urnulina																									
LIVING POPULATION <0.149 mm. and >0.074 mm.	2	0	32	0	44	18	144	5	2	11	23	19	123	8	0	0	0	3	0	0	16	16	59	279	1
Ammoastuta inepta						6																			
Ammobaculites (young)	50		63			11	88	20		9		46	2					33			6	63	37	14	
Arenoparrella mexicana																									
Elphidium (young)					100	60					35		10								88		20	81	
Haplophragmoides subinvolutum																						19			
Leptodermella variabilis																					6				
Miliammina fusca						11	6			19													43	4	
M sp.																									
Palmerinella palmerae										36		10	6												
Proteonina lagenaria												5										6			
P sp. A											52														
Recurvoides sp.																									
Rotalia (young)	50		37			6		80	50	36	13	37	82	100				67				6		.7	100
Trochammina macrescens																									
T. (young)																									
Urnulina						6	6		50													6			

in Figures 12–40. In evaluating the living population data the following qualifications should be kept in mind.

1. The samples were collected during two different seasons of the year separated by several months. It is possible that some differences in frequencies may be seasonal differences.

2. The living population is only a small fraction of the total population which includes empty tests at most places. The frequency data of the living population, therefore, are somewhat less reliable than the total population data. Species which are very low in frequency in the total population either may not be represented by living specimens, or the living specimens may show an incorrect frequency distribution. The area of the sample taken (approximately 10 sq. cm.) may be too small to give completely valid distribution data on rare species.



89°20'
89°10'
BRETON SOUND
BRETON IS
OFFSHORE SAMPLES
MISSISSIPPI
RIVER
MAIN
PASS
A LOUTRE
PASS
A
BAPTISTE COLLETTE SUBDELTA
NAUTICAL MILES
29°30'
29°20'
29°10'
89°00'

FIG. 7.—Total populations in fraction smaller than 0.149 mm.

Comparisons of living distributions with distributions of empty tests (total population, for all practical purposes) show that there is good general correlation for most species. This appears to demonstrate that either there has been little post-mortem transportation of the tests of most species for the area as a whole or the transport which has occurred has moved living and dead populations as a unit. Some of the more abundant marsh forms are an exception to this generalization, especially *Leptodermella variabilis* Parker, and also *Trochammina macrescens* H. B. Brady. These species, especially *Leptodermella variabilis*, occur in the nearshore bays although their living representatives are essentially confined to the marsh. A few other species appear to have a slightly greater range either seaward or landward from the habitats of their living populations, but this is not a striking feature of the distributions.

The size of the total living population varies within wide limits; the distributions may be seen on Figure 8. The greatest variation is seen in the marsh of Baptiste Collette Subdelta where the total living population varies from 1/sample to 513/sample over a distance of approximately ½ mile. There is also wide variation in the living population in the shallow bays, varying from 474/sample to 0/sample. Outside the bays the living populations are more uniform than in bays and marsh areas.

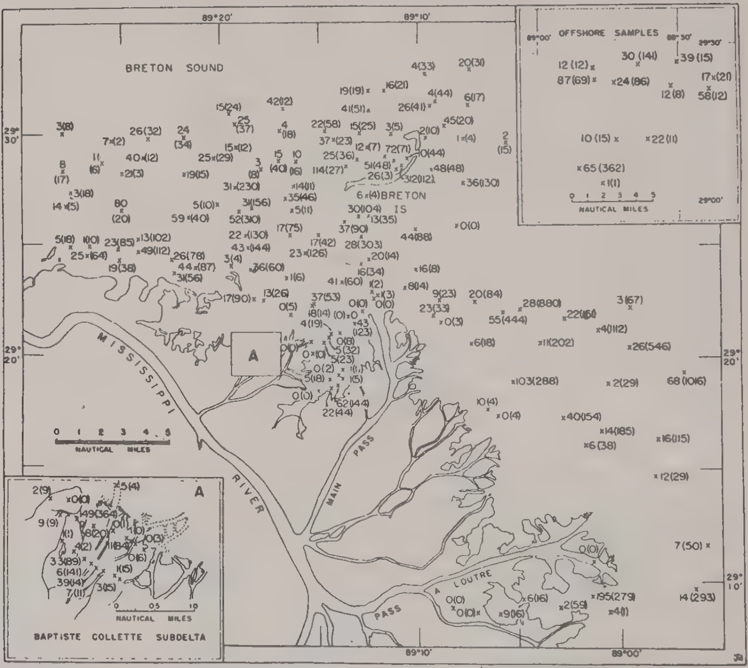

89°20'
89°10'
BRETON SOUND
BRETON IS
MISSISSIPPI RIVER
MAIN PASS
A LOUTRE PASS
A
29° 30'
29° 20'
29° 10'
89°10'
89°00'
0 1 2 3 4 5 NAUTICAL MILES
OFFSHORE SAMPLES
89°00'
88°30'
29°30'
29°00'
0 1 2 3 4 5 NAUTICAL MILES
A
0 0.5 1.0 NAUTICAL MILES
BAPTISTE COLLETTE SUBDELTA

FIG. 8.—Total living populations. Fraction larger than 0.149 mm. without parentheses; fraction smaller than 0.149 mm. in parentheses.

The northernmost, or inner, part of this area had generally the lowest standing crop of living Foraminifera at the time these collections were made, with approximately 10–50 living specimens/sample at most stations. Most bay and some

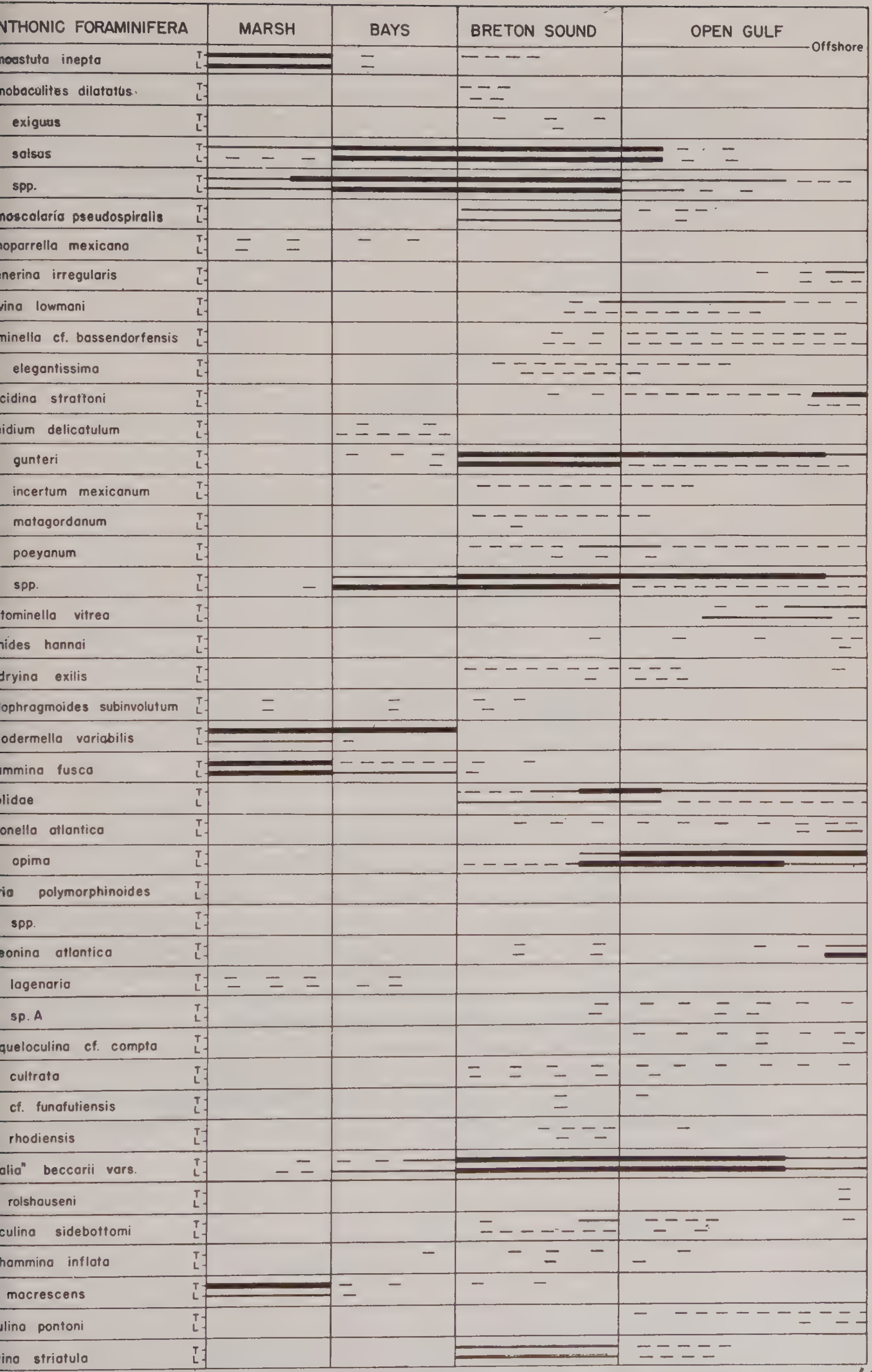


FIG. 9.—Generalized ranges of Foraminifera species; T, total population; L, living population.

marsh samples have comparable frequencies. South of Breton Island there is a larger standing crop, averaging approximately 100 or more living specimens/sample. In the vicinity of Main Pass the populations are considerably lower. The largest populations occur in the inshore part of the open-gulf stations where many populations are 500–1000 living specimens/sample. The samples farthest offshore have variable living populations of generally intermediate size.

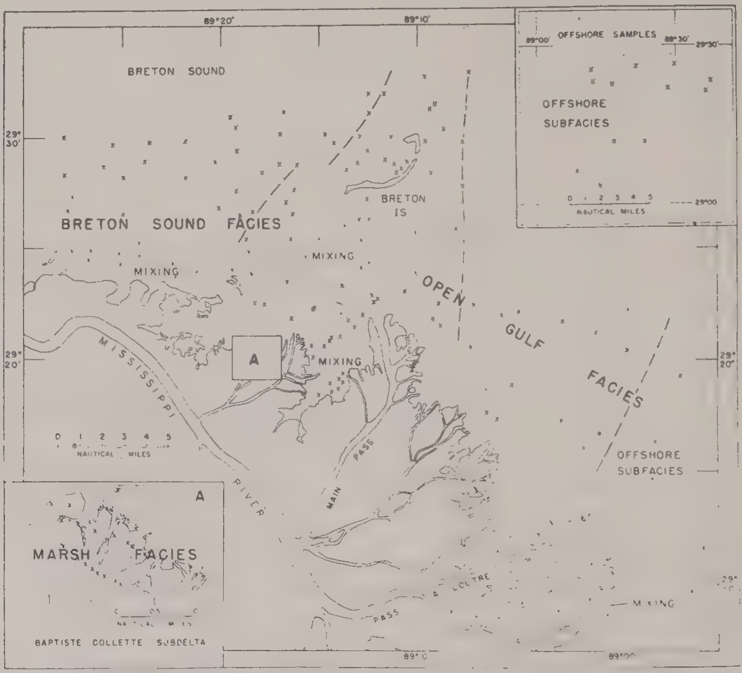

89°20'
89°10'
BRETON SOUND
29° 30'
BRETON SOUND FACIES
BRETON IS
MIXING
MIXING
OPEN GULF FACIES
MISSISSIPPI RIVER
A
MIXING
MAIN PASS
29° 20'
0 1 2 3 4 5
NAUTICAL MILES
OFFSHORE SUBFACIES
89°00'
OFFSHORE SAMPLES
88°30'
29°30'
OFFSHORE SUBFACIES
0 1 2 3 4 5
NAUTICAL MILES
29°00
A
MARSH FACIES
BAPTISTE COLLETTE SUBDELTA
A LOUTRE PASS
MIXING
89°00'

FIG. 10.—Geographic distribution of facies.

The standing crop of benthonic Foraminifera has been converted into living population/square meter of surface area by Phleger (1952, p. 347). In a nearshore area of the southern Gulf of Maine a living population varying from 1000/sq. m. to more than 100,000/sq. m., with an average of approximately 30,000/sq. m., was reported (*op. cit.*). In the outer shelf of the northwestern Gulf of Mexico the populations averaged only approximately 10,000/sq. m., from data recorded by Phleger (1951). In the present area the populations apparently vary from approximately 1000/sq. m. to more than 1,000,000/sq. m., with an average of approximately 90,000/sq. m.

There is no certainty that the present results on living populations are directly comparable with the previous ones. The rose bengal test may be a more sensitive indicator of Foraminifera which were alive at the time of collection than either the biuret test or Millon's reagent used in the previous studies. In this event, the estimates of abundances of living Foraminifera may be too low in the previous studies. The environments of the Mississippi Delta area, however, are strikingly different from either the nearshore, southwestern Gulf of Maine area or the offshore, northwestern Gulf of Mexico. The contrast in standing crop between this and the previous areas may, therefore, be a real one. Unusually high and unusually low living populations may not represent true average populations for any very large area.

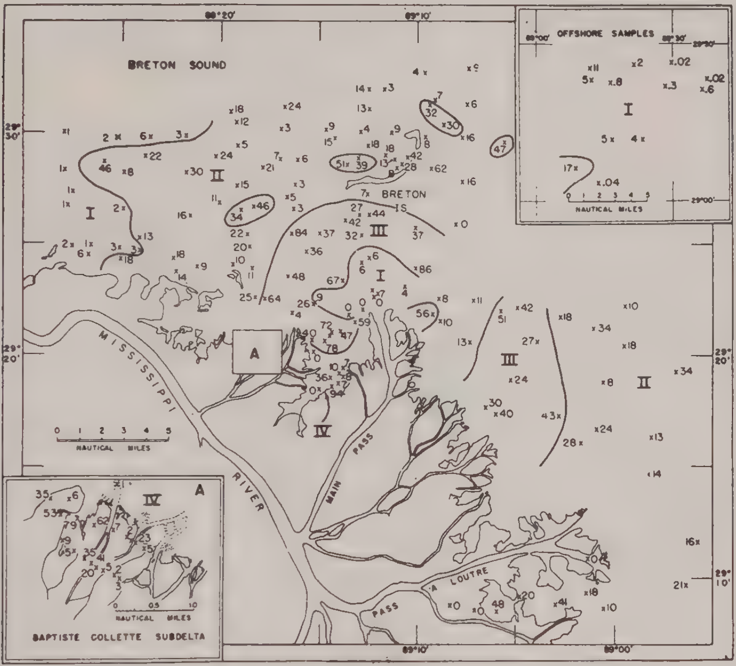

89°20'
89°10'
BRETON SOUND
OFFSHORE SAMPLES
88°00'
88°30'
29°30'
29°00'
NAUTICAL MILES
BRETON IS.
I
II
III
IV
A
MISSISSIPPI
RIVER
MAIN PASS
A LOUTRE
PASS
29°30'
29°20'
29°10'
0 1 2 3 4 5
NAUTICAL MILES
BAPTISTE COLLETTE SUBDELTA
0 0.5 1.0
NAUTICAL MILES
89°10'
89°00'

FIG. 11.—Abundance of living populations in per cent of total populations (both living and dead).

It is surprising that an area such as this can support such a large standing crop of living Foraminifera. The only apparent areas of low living population are directly off the active passes in the area sampled. It seems reasonable that the standing crop of Foraminifera may be related to the general organic production in any area. This suggests that the area covered either is one of high organic production or the high living Foraminifera population is supported by organic materials brought in by the streams.

The possibility of using the ratio of living specimens and total population as a measure of relative rate of sedimentation has been discussed and illustrated by Phleger (1951, p. 65). Recently W. R. Walton (ms.) has successfully used the percentage relationship of living and dead populations to illustrate different relative rates of sedimentation in Todos Santos Bay, Baja California. The abundance of living populations in per cent of total population (both living and dead) is plotted for each Mississippi Delta station in Figure 11. It may be assumed that the standing crop is indicative of the rate at which Foraminifera are being produced. A large standing crop relative to the total population should indicate relatively rapid dilution with sediment, and a small crop relative to the total population should indicate a slow rate of supply of sediment.

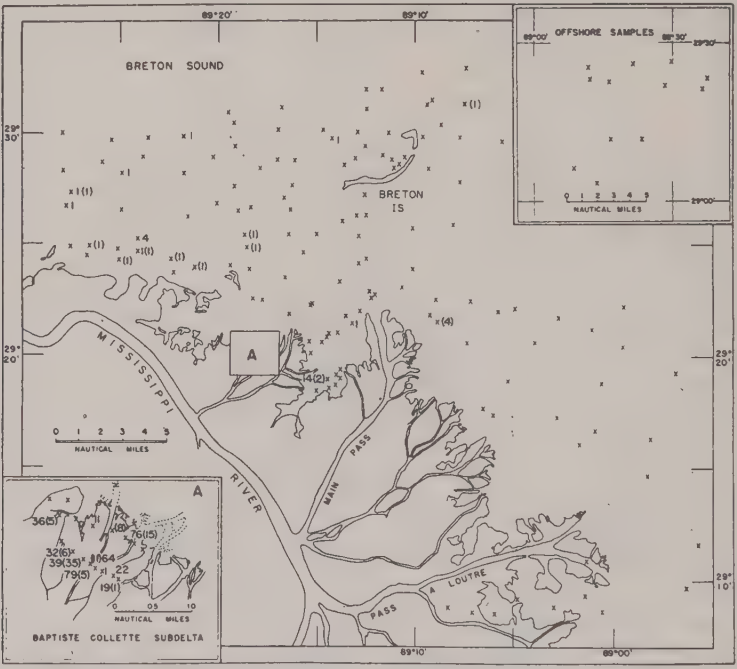

89°20'
89°10'
OFFSHORE SAMPLES
89°00'
88°30'
29°30'
29°00'
0 1 2 3 4 5
NAUTICAL MILES
BRETON SOUND
29° 30'
BRETON IS
29° 20'
29° 10'
MISSISSIPPI RIVER
MAIN PASS
A LOUTRE PASS
A
x(1)
x4
x(4)
4(2)
36(5)
32(6)
39(35)
1064
79(5)
76(15)
(8)
22
19(1)
0 05 10
NAUTICAL MILES
BAPTISTE COLLETTE SUBDELTA
89°10'
89°00'

FIG. 12.—Distribution of *Ammoastuta inepta* (Cushman and McCulloch) in per cent of total population. Per cent of fraction larger than 0.149 mm. without parentheses; per cent of fraction smaller than 0.149 mm. in parentheses.

The distribution of the living population in per cent of total population seems to be divisible into four frequency types which have an areal distribution; these are indicated in Figure 11 by roman numerals. Low ratios of living to total populations (I) are seen at the westernmost edge of the area sampled in Breton Sound, in the samples farthest offshore and directly off Main Pass. Intermediate per cent areas (II) constitute most of Breton Sound which was sampled and most of the

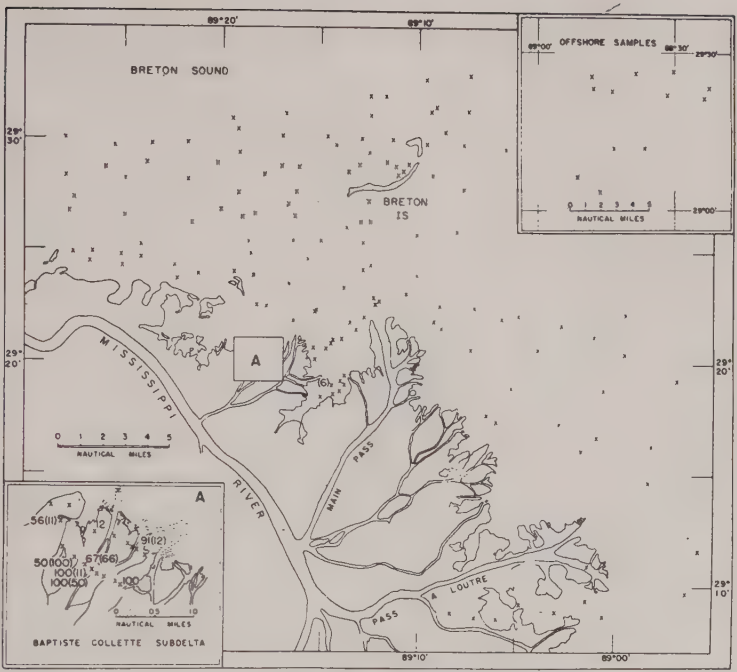

89°20'
89°10'
BRETON SOUND
29° 30'
29° 20'
OFFSHORE SAMPLES
89°00'
88°30'
29°30'
29°00'
0 1 2 3 4 5
NAUTICAL MILES
BRETON IS
MISSISSIPPI
RIVER
MAIN PASS
A LOUTRE
PASS
A
(6)
29° 20'
29° 10'
89°10'
89°00'
56(11)
12
9(12)
50(100)
67(66)
100(11)
100(50)
100
0 0.5 1.0
NAUTICAL MILES
BAPTISTE COLLETTE SUBDELTA

FIG. 13.—Distribution of *Ammoastuta inepta* (Cushman and McCulloch) in per cent of living population. Per cent of fraction larger than 0.149 mm. without parentheses; per cent of fraction smaller than 0.149 mm. in parentheses.

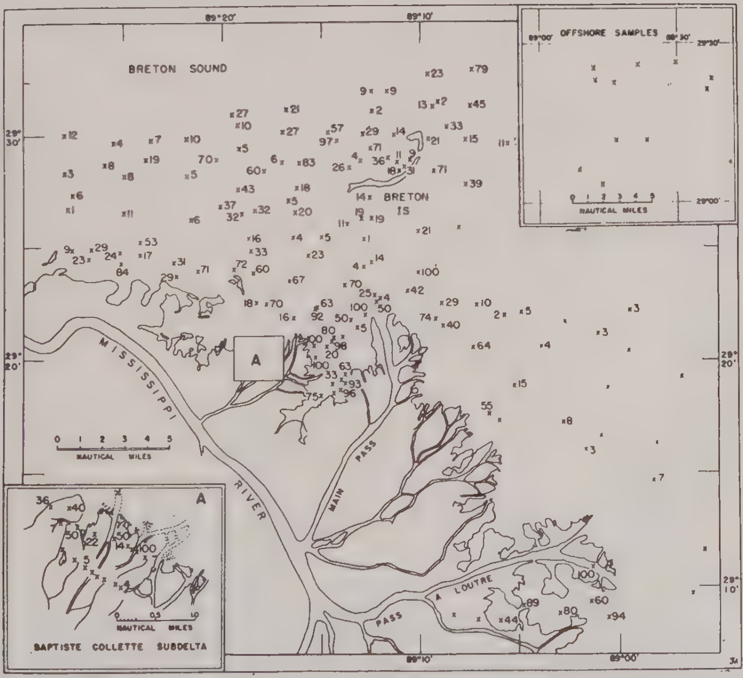

89°20'
89°10'
BRETON SOUND
29° 30'
29° 20'
OFFSHORE SAMPLES
89°00'
88°30'
29°30'
29°00'
0 1 2 3 4 5
NAUTICAL MILES
BRETON IS
MISSISSIPPI
RIVER
MAIN PASS
A LOUTRE
PASS
A
23
79
9
9
27
21
2
13
45
10
57
29
14
33
12
4
7
10
27
97
21
15
70
5
71
19
6
83
26
36
11
9
3
8
8
5
60
18
31
71
39
6
43
18
14
1
11
37
32
5
6
32
20
19
19
21
53
16
4
5
1
9
29
17
33
23
14
23
24
31
84
71
29
72
60
4
100
67
70
42
25
4
18
70
63
100
50
29
10
5
3
16
92
50
74
2
80
5
40
3
100
98
64
4
20
100
63
33
93
15
75
96
55
8
3
7
100
60
89
80
44
94
36
40
50
50
22
14
100
5
0 0.5 1.0
NAUTICAL MILES
BAPTISTE COLLETTE SUBDELTA
29° 20'
29° 10'
89°10'
89°00'

FIG. 14.—Distribution of *Ammobaculites salsus* Cushman and Bronnimann in per cent of total population. All specimens larger than 0.149 mm.

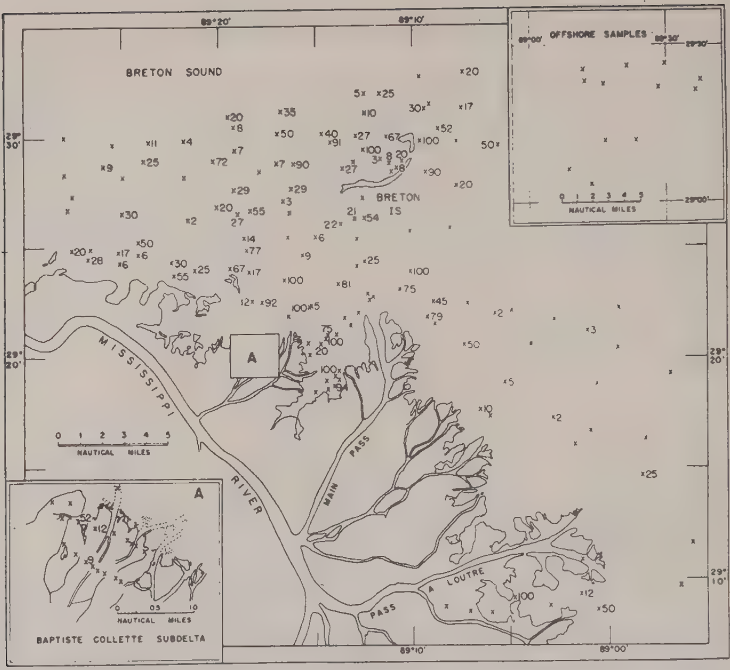

BRETON SOUND
OFFSHORE SAMPLES
BRETON IS
MISSISSIPPI RIVER
MAIN PASS
A LOUTRE PASS
A
NAUTICAL MILES
BAPTISTE COLLETTE SUBDELTA
89°20'
89°10'
89°00'
89°30'
29°30'
29°20'
29°10'
29°00'

FIG. 15.—Distribution of *Ammobaculites salsus* Cushman and Bronnimann in per cent of living population. All specimens larger than 0.149 mm.

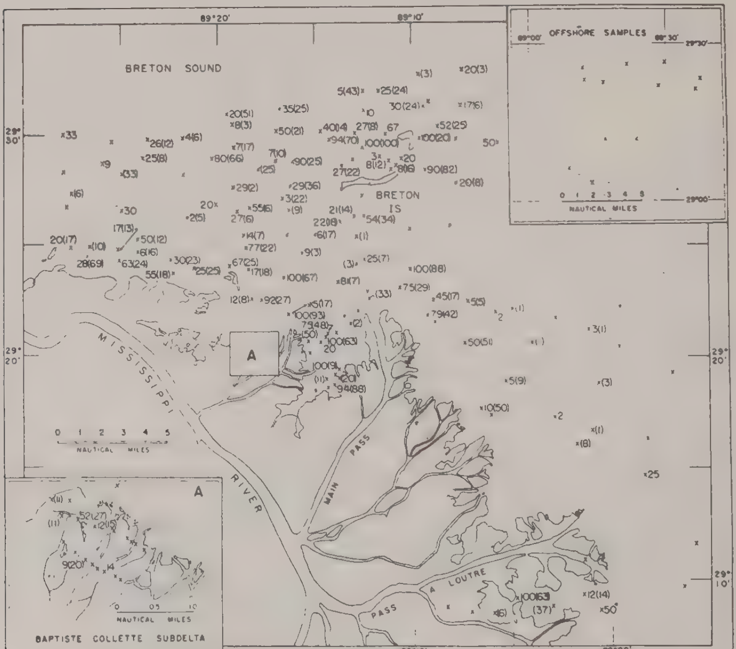

BRETON SOUND
OFFSHORE SAMPLES
BRETON IS
MISSISSIPPI RIVER
MAIN PASS
A LOUTRE PASS
A
NAUTICAL MILES
BAPTISTE COLLETTE SUBDELTA
89°20'
89°10'
89°00'
89°30'
29°30'
29°20'
29°10'
29°00'

FIG. 16.—Distribution of *Ammobaculites* spp. in per cent of living population. Per cent of fraction larger than 0.149 mm. without parentheses; per cent of fraction smaller than 0.149 mm. in parentheses.

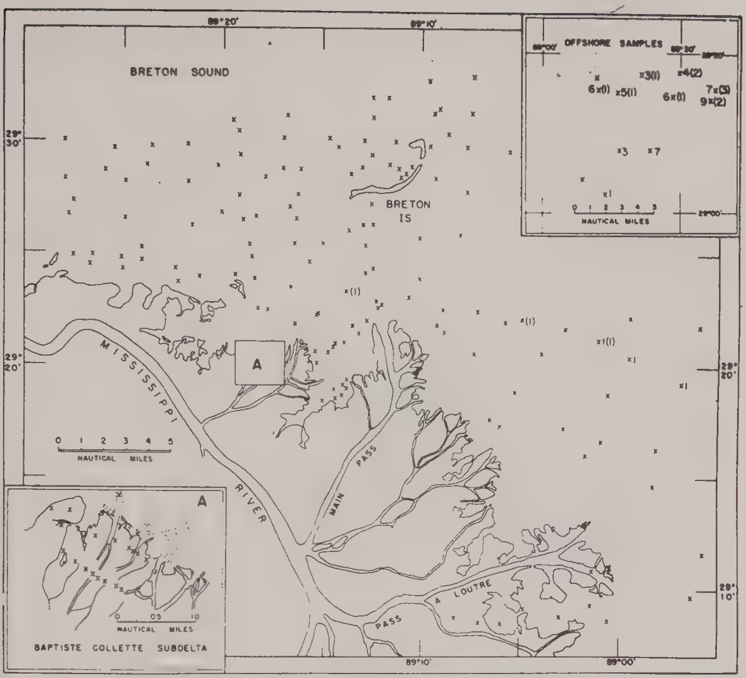

89°20'
89°10'
BRETON SOUND
29° 30'
29° 20'
29° 10'
BRETON IS
MISSISSIPPI RIVER
MAIN PASS
PASS A LOUTRE
A
0 1 2 3 4 5
NAUTICAL MILES
OFFSHORE SAMPLES
89°00'
88°30'
29°30'
29°00'
x3(1)
x4(2)
6x(1)
x5(1)
6x(1)
7x(5)
9x(2)
x3
x7
x1
x(1)
x(1)
x1(1)
x1
x1
BAPTISTE COLLETTE SUBDELTA
0 05 10
89°10'
89°00'

FIG. 17.—Distribution of *Bigenerina irregularis* Phleger and Parker in per cent of total population. Per cent of fraction larger than 0.149 mm. without parentheses; per cent of fraction smaller than 0.149 mm. in parentheses.

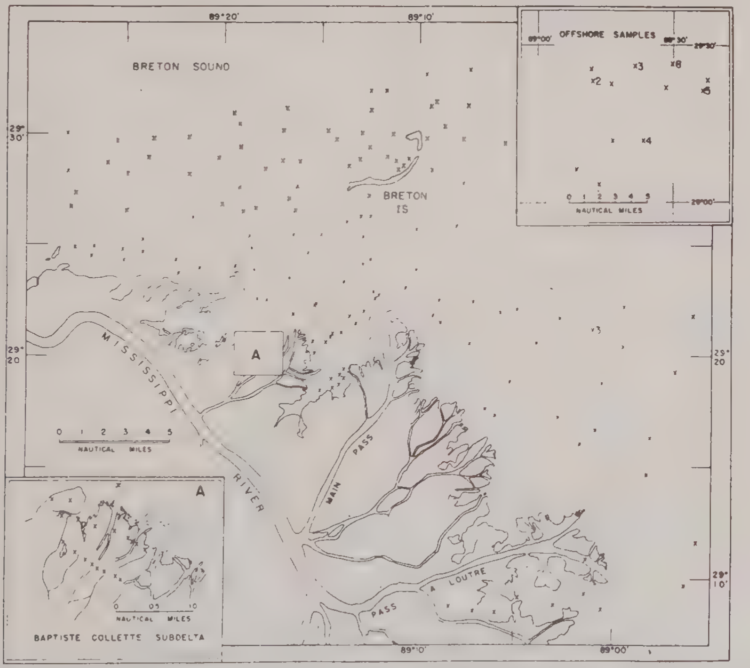

89°20'
89°10'
BRETON SOUND
29° 30'
29° 20'
29° 10'
BRETON IS
MISSISSIPPI RIVER
MAIN PASS
PASS A LOUTRE
A
0 1 2 3 4 5
NAUTICAL MILES
OFFSHORE SAMPLES
89°00'
88°30'
29°30'
29°00'
x3
x8
x2
x5
x4
x3
BAPTISTE COLLETTE SUBDELTA
0 05 10
89°10'
89°00'

FIG. 18.—Distribution of *Bigenerina irregularis* Phleger and Parker in per cent of living population. All specimens larger than 0.149 mm.

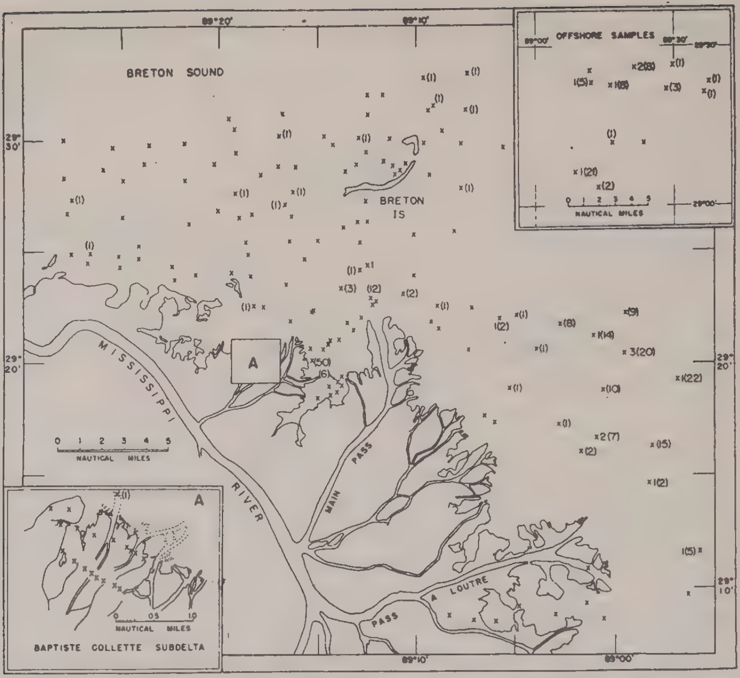

BRETON SOUND
OFFSHORE SAMPLES
BRETON IS
MISSISSIPPI RIVER
MAIN PASS
PASS A LOUTRE
A
BAPTISTE COLLETTE SUBDELTA
NAUTICAL MILES
89°20'
89°10'
89°00'
29° 30'
29° 20'
29° 10'
(50)
(6)
3(20)
1(22)
1(14)
(8)
(9)
(10)
2(7)
(15)
1(2)
1(5)

FIG. 19.—Distribution of *Buliminella* cf. *bassendorfensis* Cushman and Parker in per cent of total population. Per cent of fraction larger than 0.149 mm. without parentheses; per cent of fraction smaller than 0.149 mm. in parentheses.

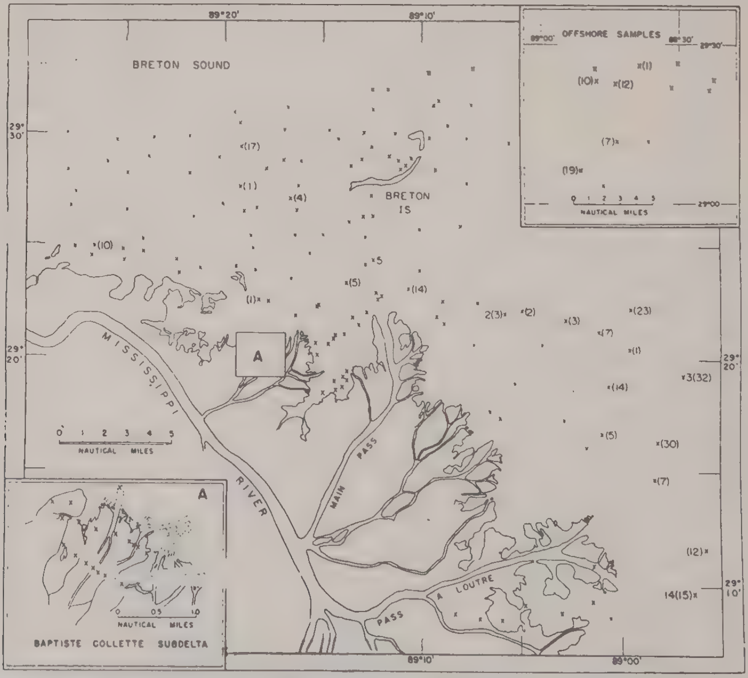

BRETON SOUND
OFFSHORE SAMPLES
BRETON IS
MISSISSIPPI RIVER
MAIN PASS
PASS A LOUTRE
A
BAPTISTE COLLETTE SUBDELTA
NAUTICAL MILES
89°20'
89°10'
89°00'
29° 30'
29° 20'
29° 10'
(17)
(10)
(14)
(23)
3(32)
(30)
(12)
14(15)
(19)

FIG. 20.—Distribution of *Buliminella* cf. *bassendorfensis* Cushman and Parker in per cent of living population. Per cent of fraction larger than 0.149 mm. without parentheses; per cent of fraction smaller than 0.149 mm. in parentheses.

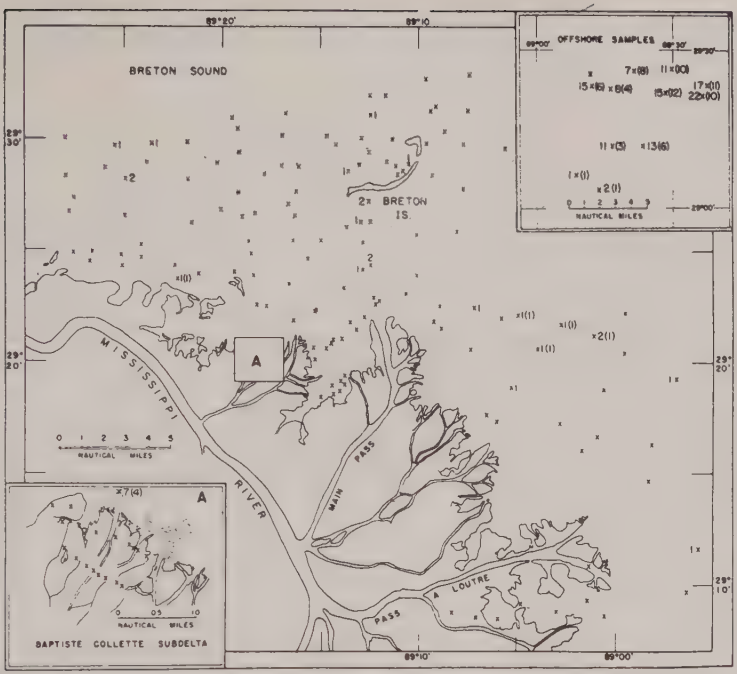

89°20'
89°10'
OFFSHORE SAMPLES
89°00'
88°30'
29°30'
7(8)
11(10)
15(6)
8(4)
15(12)
17(11)
22(10)
11(3)
13(6)
1(1)
2(1)
0 1 2 3 4 5
NAUTICAL MILES
29°00'
BRETON SOUND
29° 30'
1
1
2
BRETON IS.
2
2
1(1)
1
1(1)
1(1)
2(1)
1(1)
29° 20'
A
MISSISSIPPI RIVER
MAIN PASS
PASS A LOUTRE
1
1
0 1 2 3 4 5
NAUTICAL MILES
7(4)
A
0 0.5 1.0
NAUTICAL MILES
BAPTISTE COLLETTE SUBDELTA
29° 10'
89°10'
89°00'

FIG. 21.—Distribution of *Cibicidina strattoni* (Applin) in per cent of total population. Per cent of fraction larger than 0.149 mm. without parentheses; per cent of fraction smaller than 0.149 mm. in parentheses.

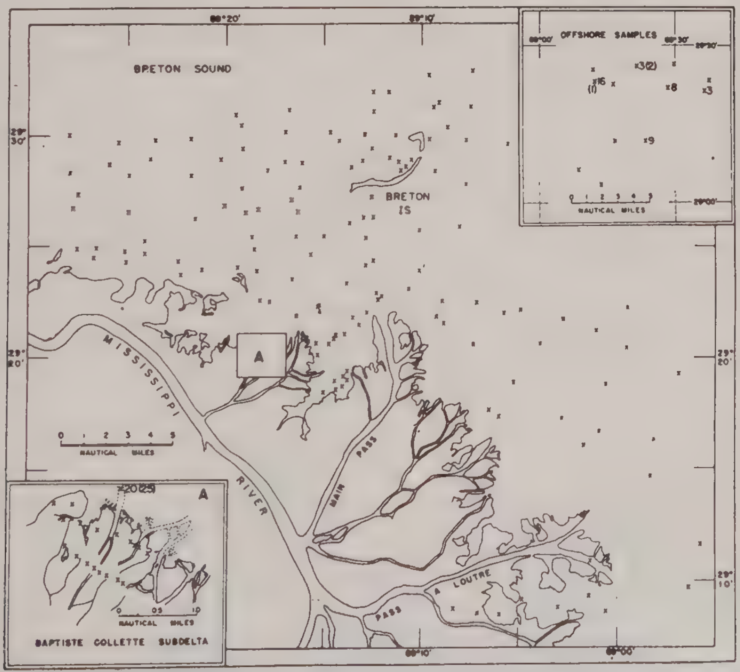

89°20'
89°10'
OFFSHORE SAMPLES
89°00'
88°30'
29°30'
3(2)
16
(1)
8
3
9
0 1 2 3 4 5
NAUTICAL MILES
29°00'
BRETON SOUND
29° 30'
BRETON IS.
29° 20'
A
MISSISSIPPI RIVER
MAIN PASS
PASS A LOUTRE
0 1 2 3 4 5
NAUTICAL MILES
20(25)
A
0 0.5 1.0
NAUTICAL MILES
BAPTISTE COLLETTE SUBDELTA
29° 10'
89°10'
89°00'

FIG. 22.—Distribution of *Cibicidina strattoni* (Applin) in per cent of living population. Per cent of fraction larger than 0.149 mm. without parentheses; per cent of fraction smaller than 0.149 mm. in parentheses.

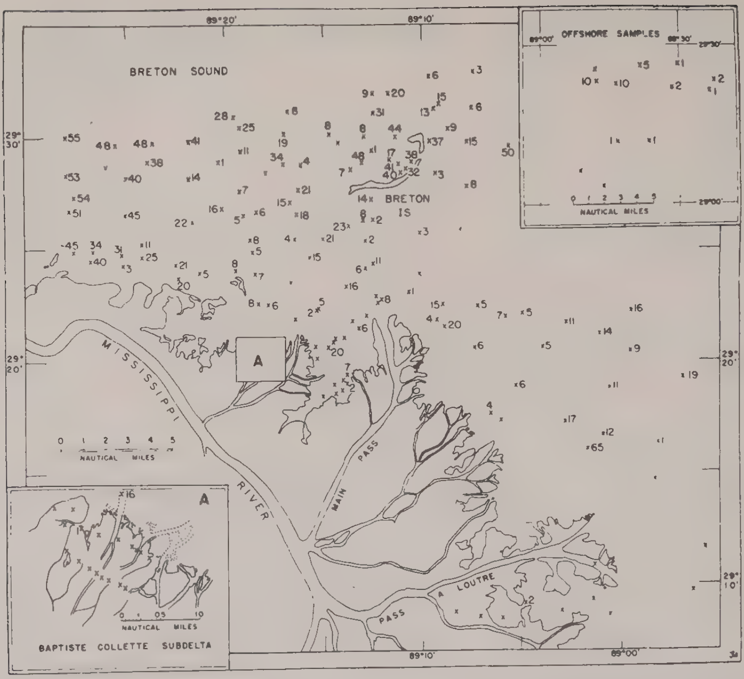

89°20'
89°10'
BRETON SOUND
29° 30'
29° 20'
29° 10'
BRETON IS
MISSISSIPPI RIVER
MAIN PASS
A LOUTRE PASS
A
0 1 2 3 4 5
NAUTICAL MILES
OFFSHORE SAMPLES
89°00'
88°30'
29°30'
29°00'
BAPTISTE COLLETTE SUBDELTA
0 0.5 1.0
NAUTICAL MILES
89°10'
89°00'

FIG. 23.—Distribution of *Elphidium gunteri* Cole in per cent of total population. All specimens larger than 0.149 mm.

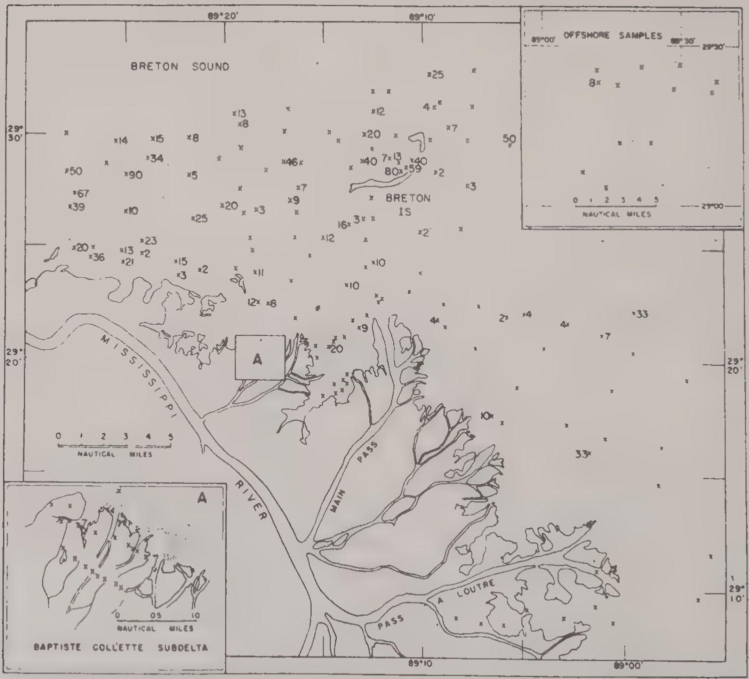

89°20'
89°10'
BRETON SOUND
29° 30'
29° 20'
29° 10'
BRETON IS
MISSISSIPPI RIVER
MAIN PASS
A LOUTRE PASS
A
0 1 2 3 4 5
NAUTICAL MILES
OFFSHORE SAMPLES
89°00'
88°30'
29°30'
29°00'
BAPTISTE COLLETTE SUBDELTA
0 0.5 1.0
NAUTICAL MILES
89°10'
89°00'

FIG. 24.—Distribution of *Elphidium gunteri* Cole in per cent of living population. All specimens larger than 0.149 mm.

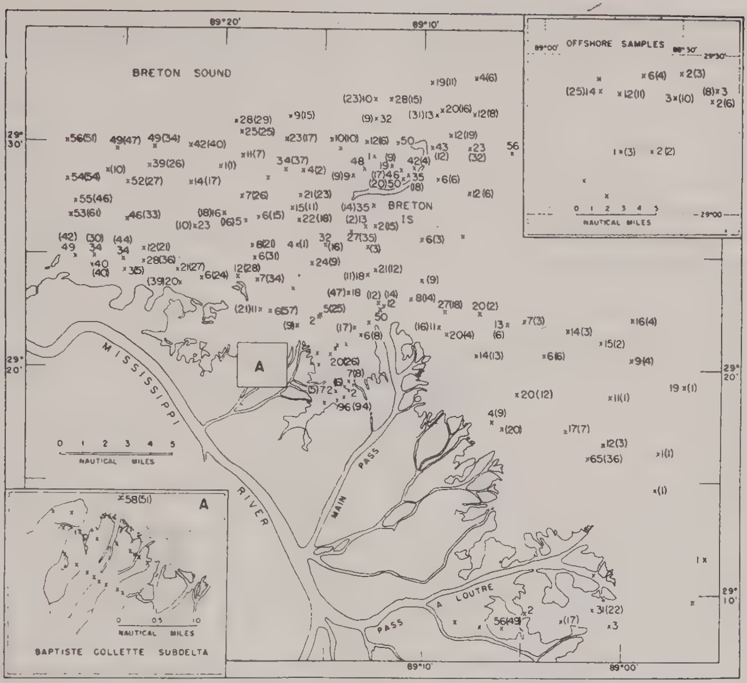

89°20'
89°10'
89°00'
29° 30'
29° 20'
29° 10'
BRETON SOUND
OFFSHORE SAMPLES
BRETON IS
MISSISSIPPI
RIVER
MAIN PASS
PASS A LOUTRE
A
BAPTISTE COLLETTE SUBDELTA
NAUTICAL MILES

FIG. 25.—Distribution of *Elphidium* spp. in per cent of total population. Per cent of fraction larger than 0.149 mm. without parentheses; per cent of fraction smaller than 0.149 mm. in parentheses.

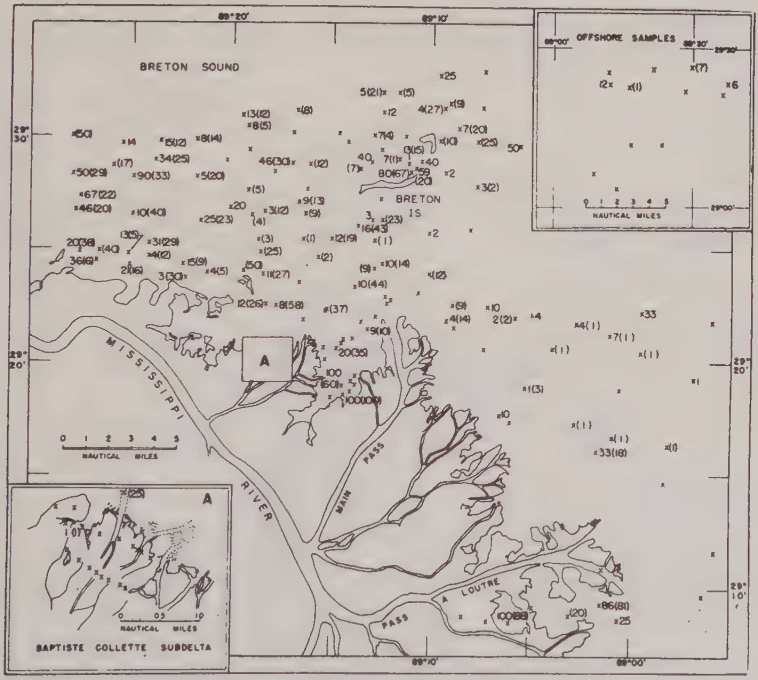

89°20'
89°10'
89°00'
29° 30'
29° 20'
29° 10'
BRETON SOUND
OFFSHORE SAMPLES
BRETON IS
MISSISSIPPI
RIVER
MAIN PASS
PASS A LOUTRE
A
BAPTISTE COLLETTE SUBDELTA
NAUTICAL MILES

FIG. 26.—Distribution of *Elphidium* spp. in per cent of living population. Per cent of fraction larger than 0.149 mm. without parentheses; per cent of fraction smaller than 0.149 mm. in parentheses.

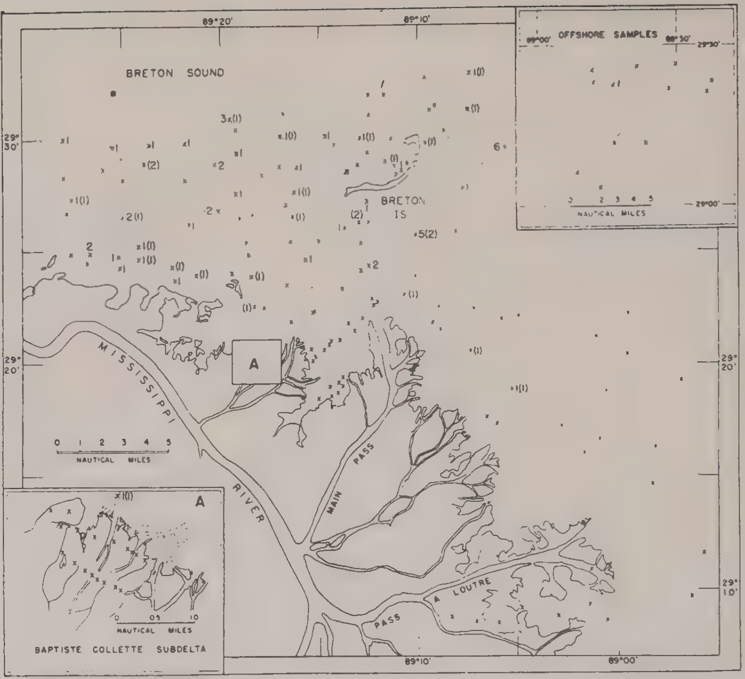

89°20'
89°10'
OFFSHORE SAMPLES
89°00'
88°30'
29°30'
29°00'
NAUTICAL MILES
BRETON SOUND
BRETON IS
29° 30'
29° 20'
29° 10'
MISSISSIPPI RIVER
MAIN PASS
PASS A LOUTRE
A
0 1 2 3 4 5
NAUTICAL MILES
BAPTISTE COLLETTE SUBDELTA
0 0.5 1.0
89°10'
89°00'

FIG. 27.—Distribution of *Gaudryina exilis* Cushman and Bronnimann in per cent of total population. Per cent of fraction larger than 0.149 mm. without parentheses; per cent of fraction smaller than 0.149 mm. in parentheses.

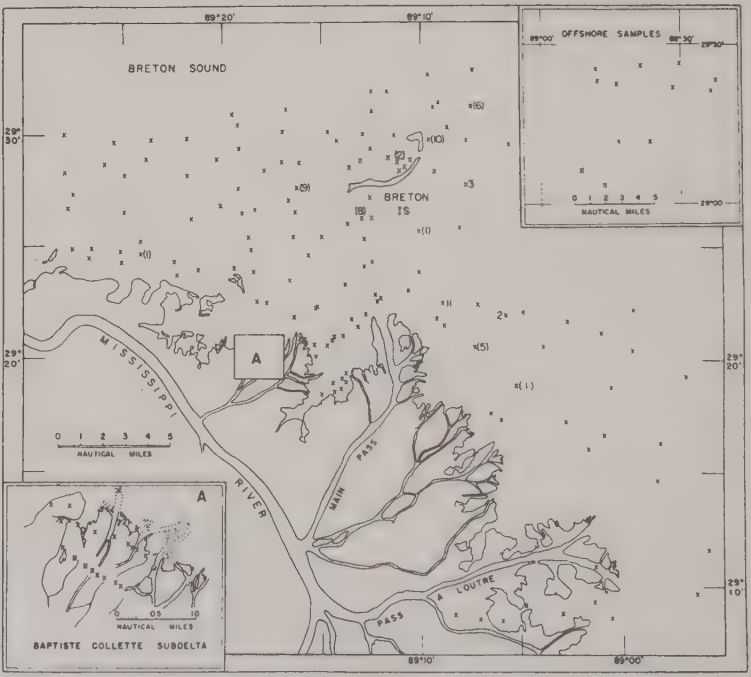

89°20'
89°10'
OFFSHORE SAMPLES
89°00'
88°30'
29°30'
29°00'
NAUTICAL MILES
BRETON SOUND
BRETON IS
29° 30'
29° 20'
29° 10'
MISSISSIPPI RIVER
MAIN PASS
PASS A LOUTRE
A
0 1 2 3 4 5
NAUTICAL MILES
BAPTISTE COLLETTE SUBDELTA
0 0.5 1.0
89°10'
89°00'

FIG. 28.—Distribution of *Gaudryina exilis* Cushman and Bronnimann in per cent of living population. Per cent of fraction larger than 0.149 mm. without parentheses; per cent of fraction smaller than 0.149 mm. in parentheses.

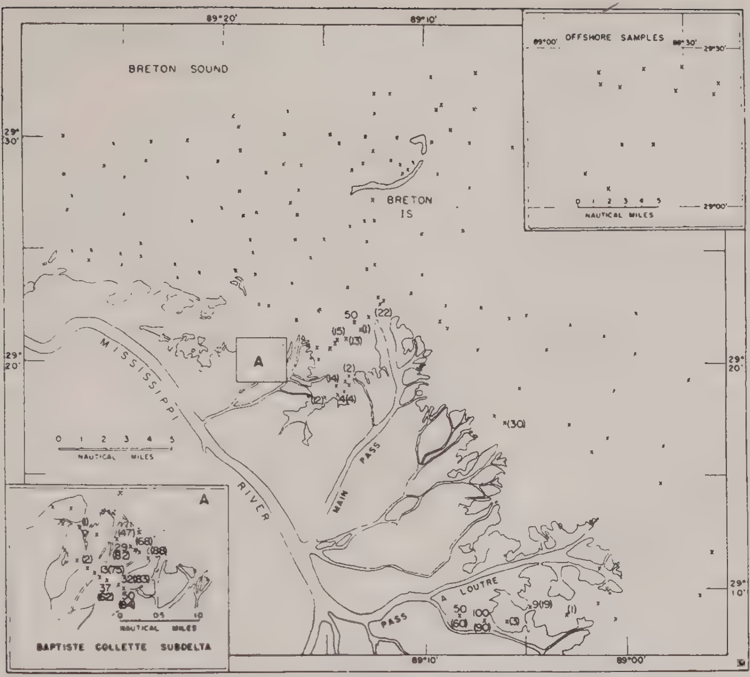

89°20'
89°10'
OFFSHORE SAMPLES
89°00'
88°30'
29°30'
29°00'
0 1 2 3 4 5
NAUTICAL MILES
BRETON SOUND
29° 30'
BRETON IS
50
(22)
(15)
(1)
(13)
(2)
(4)
(2)
4(4)
(30)
29° 20'
MISSISSIPPI
RIVER
MAIN PASS
A
0 1 2 3 4 5
NAUTICAL MILES
(47)
(68)
29
(82)
(88)
(2)
3(75)
37
(62)
32(83)
50
(84)
0 0.5 1.0
NAUTICAL MILES
BAPTISTE COLLETTE SUBDELTA
A LOUTRE
PASS
50
(60)
100
(90)
(3)
9(19)
(1)
29° 10'
89°10'
89°00'

FIG. 29.—Distribution of *Leptodermella variabilis* Parker in per cent of total population. Per cent of fraction larger than 0.149 mm. without parentheses; per cent of fraction smaller than 0.149 mm. in parentheses.

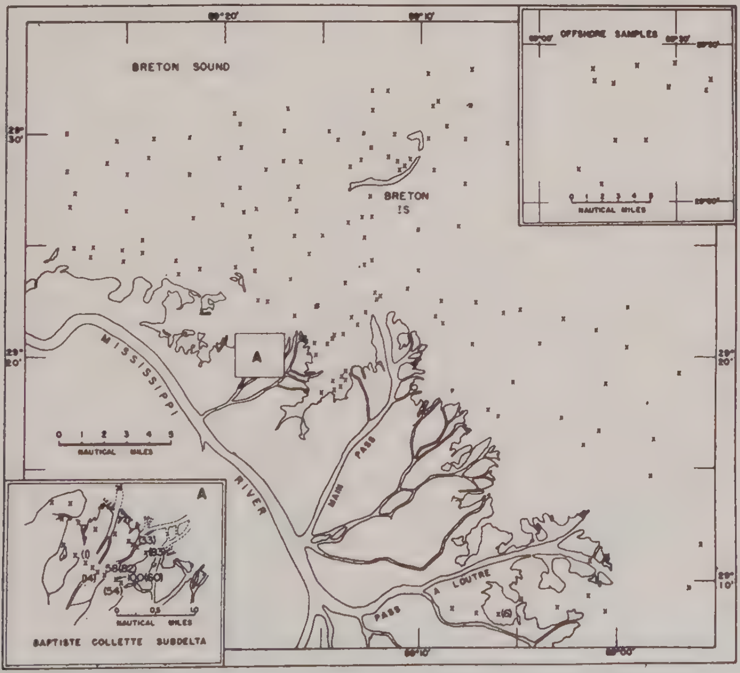

89°20'
89°10'
OFFSHORE SAMPLES
89°00'
88°30'
29°30'
29°00'
0 1 2 3 4 5
NAUTICAL MILES
BRETON SOUND
29° 30'
BRETON IS
29° 20'
MISSISSIPPI
RIVER
MAIN PASS
A
0 1 2 3 4 5
NAUTICAL MILES
(33)
(83)
(1)
58(82)
(14)
100(60)
(54)
0 0.5 1.0
NAUTICAL MILES
BAPTISTE COLLETTE SUBDELTA
A LOUTRE
PASS
(6)
29° 10'
89°10'
89°00'

FIG. 30.—Distribution of *Leptodermella variabilis* Parker in per cent of living population. Per cent of fraction larger than 0.149 mm. without parentheses; per cent of fraction smaller than 0.149 mm. in parentheses.

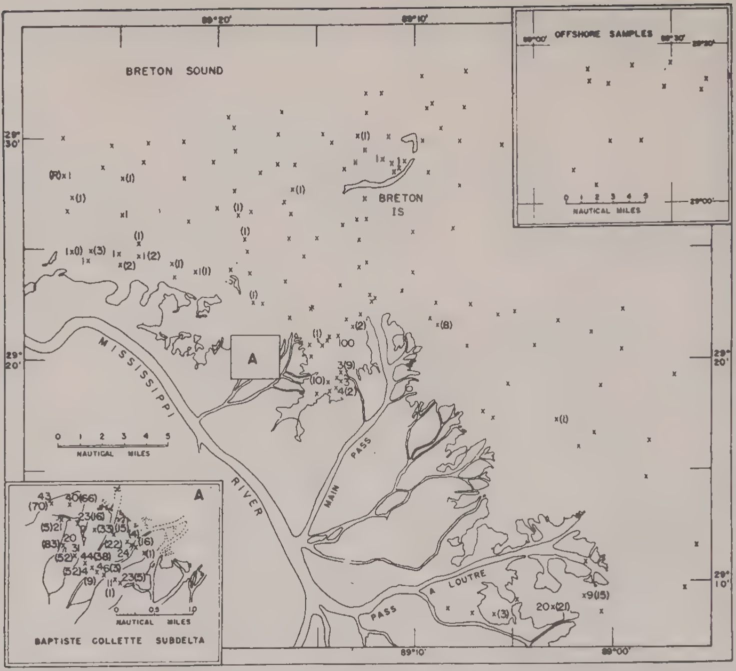

89°20'
89°10'
BRETON SOUND
29° 30'
BRETON IS
29° 20'
MISSISSIPPI
RIVER
MAIN PASS
A LOUTRE
PASS
0 1 2 3 4 5
NAUTICAL MILES
29° 10'
89°10'
89°00'
OFFSHORE SAMPLES
89°00'
88°30'
29°30'
29°00'
A
BAPTISTE COLLETTE SUBDELTA
0 0.5 1.0
NAUTICAL MILES
100
3(9)
(10)
4(2)
(8)
9(15)
20(21)
(3)
43
(70)
40(66)
23(16)
(5)21
20
(83)
31
(52)
44(38)
(52)4
46(3)
(9)
11
23(5)
(1)
(22)
24
(16)

FIG. 31.—Distribution of *Miliammina fusca* (H. B. Brady) in per cent of total population. Per cent of fraction larger than 0.149 mm. without parentheses; per cent of fraction smaller than 0.149 mm. in parentheses.

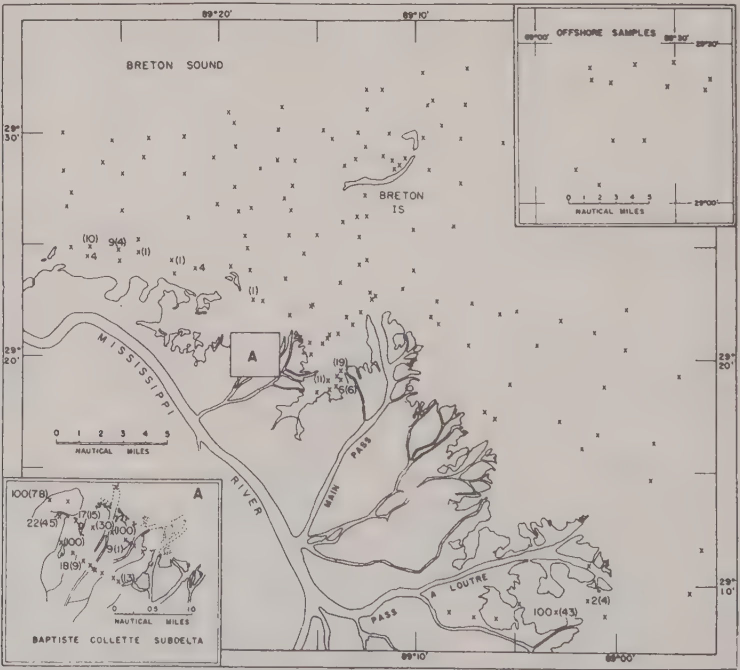

89°20'
89°10'
BRETON SOUND
29° 30'
BRETON IS
29° 20'
MISSISSIPPI
RIVER
MAIN PASS
A LOUTRE
PASS
0 1 2 3 4 5
NAUTICAL MILES
29° 10'
89°10'
89°00'
OFFSHORE SAMPLES
89°00'
88°30'
29°30'
29°00'
A
BAPTISTE COLLETTE SUBDELTA
0 0.5 1.0
NAUTICAL MILES
(10)
9(4)
4
(1)
4
(19)
(11)
6(6)
2(4)
100(43)
100(78)
22(45)
17(15)
(30)
(100)
(100)
9(1)
18(9)
(13)

FIG. 32.—Distribution of *Miliammina fusca* (H. B. Brady) in per cent of living population. Per cent of fraction larger than 0.149 mm. without parentheses; per cent of fraction smaller than 0.149 mm. in parentheses.

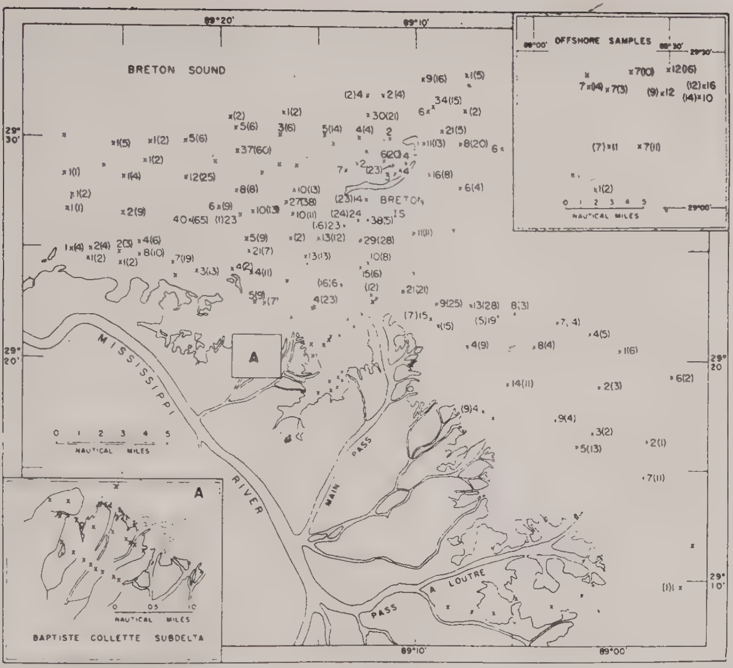

89°20'
89°10'
OFFSHORE SAMPLES
BRETON SOUND
BRETON IS
MISSISSIPPI RIVER
MAIN PASS
A LOUTRE PASS
A
BAPTISTE COLLETTE SUBDELTA
NAUTICAL MILES
29° 30'
29° 20'
29° 10'
89°00'

FIG. 33.—Distribution of Miliolidae in per cent of total population. Per cent of fraction larger than 0.149 mm. without parentheses; per cent of fraction smaller than 0.149 mm. in parentheses.

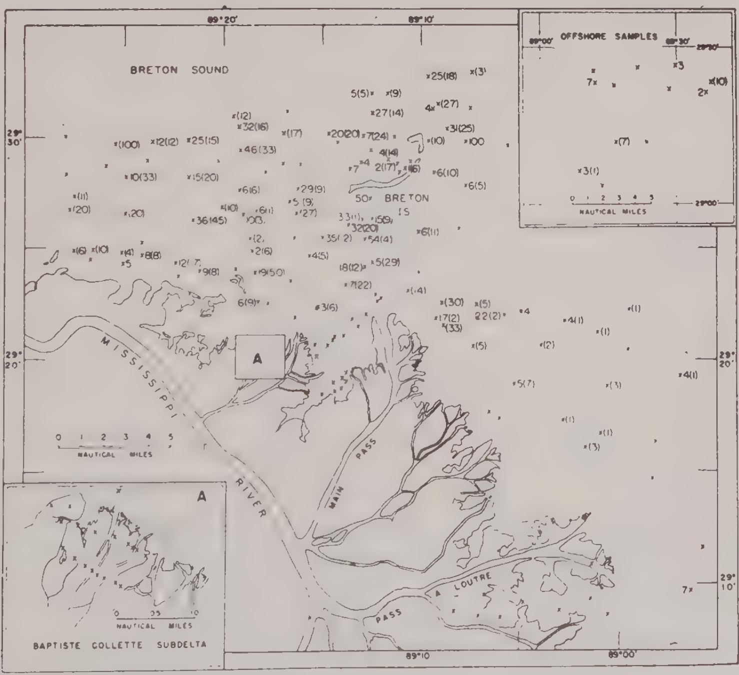

89°20'
89°10'
OFFSHORE SAMPLES
BRETON SOUND
BRETON IS
MISSISSIPPI RIVER
MAIN PASS
A LOUTRE PASS
A
BAPTISTE COLLETTE SUBDELTA
NAUTICAL MILES
29° 30'
29° 20'
29° 10'
89°00'

FIG. 34.—Distribution of Miliolidae in per cent of living population. Per cent of fraction larger than 0.149 mm. without parentheses; per cent of fraction smaller than 0.149 mm. in parentheses.

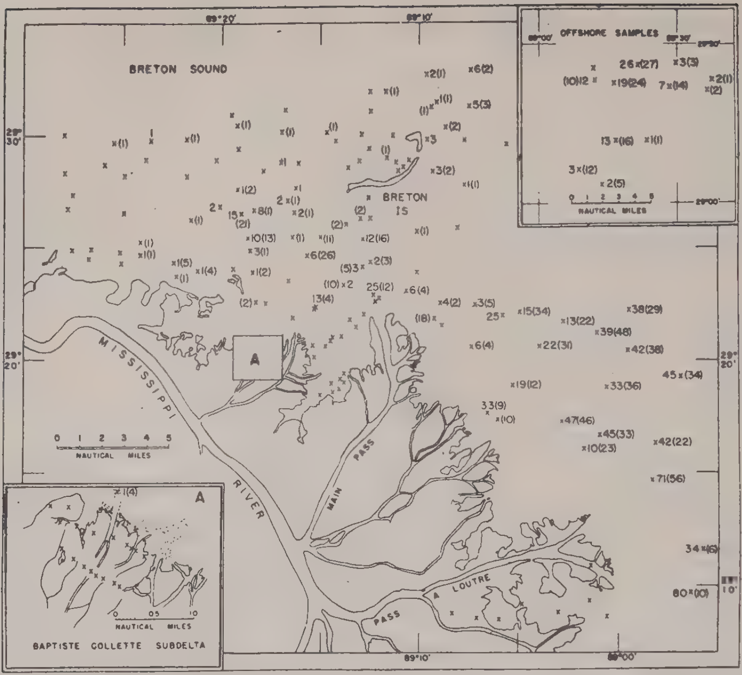

89°20'
89°10'
BRETON SOUND
BRETON IS
OFFSHORE SAMPLES
89°00'
88°30'
29°30'
29°00'
NAUTICAL MILES
29° 30'
29° 20'
29° 10'
MISSISSIPPI RIVER
MAIN PASS
PASS A LOUTRE
A
BAPTISTE COLLETTE SUBDELTA
0 1 2 3 4 5
0 0.5 1.0
x2(1)
x6(2)
x5(3)
x3(2)
x12(16)
x6(26)
x10(13)
25(12)
x6(4)
13(4)
x4(2)
x3(5)
x15(34)
x13(22)
x38(29)
x39(48)
x42(38)
x22(31)
x6(4)
45x(34)
x19(12)
x33(36)
33(9)
x47(46)
x45(33)
x10(23)
x42(22)
x71(56)
34x(6)
80x(10)
26x(27)
x3(3)
x19(24)
7x(14)
13x(16)
3x(12)
x2(5)

FIG. 35.—Distribution of *Nonionella opima* Cushman in per cent of total population. Per cent of fraction larger than 0.149 mm. without parentheses; per cent of fraction smaller than 0.149 mm. in parentheses.

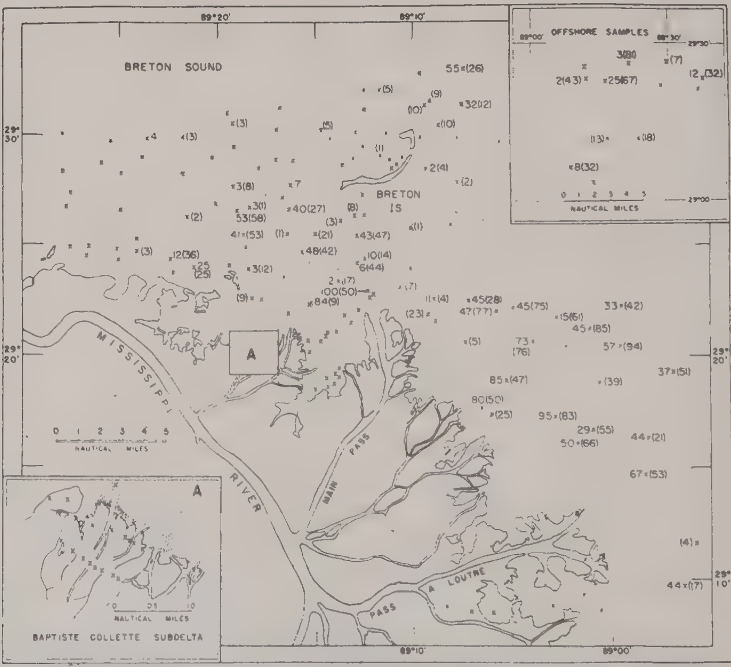

89°20'
89°10'
BRETON SOUND
BRETON IS
OFFSHORE SAMPLES
89°00'
88°30'
29°30'
29°00'
NAUTICAL MILES
29° 30'
29° 20'
29° 10'
MISSISSIPPI RIVER
MAIN PASS
PASS A LOUTRE
A
BAPTISTE COLLETTE SUBDELTA
0 1 2 3 4 5
0 0.5 1.0
55x(26)
x32(12)
x2(4)
x40(27)
53(58)
41x(53)
x43(47)
x48(42)
12(36)
100(50)
x84(9)
x45(28)
47(77)
x45(75)
33x(42)
x15(61)
45x(85)
57x(94)
73x(76)
85x(47)
80(50)
x(25)
95x(83)
29x(55)
50x(66)
44x(21)
37x(51)
67x(53)
44x(17)
3(8)
2(43)
x25(67)
12x(32)
x8(32)

FIG. 36.—Distribution of *Nonionella opima* Cushman in per cent of living population. Per cent of fraction larger than 0.149 mm. without parentheses; per cent of fraction smaller than 0.149 mm. in parentheses.

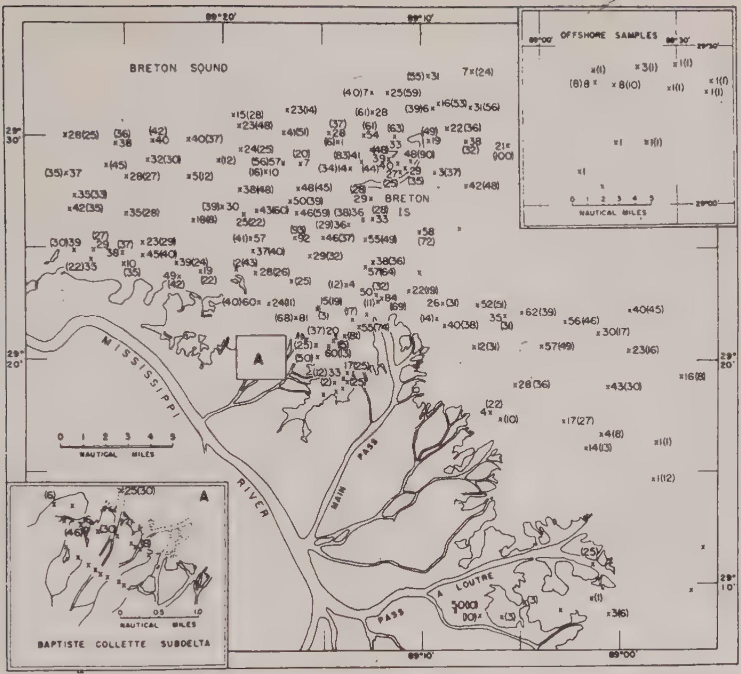

BRETON SOUND
OFFSHORE SAMPLES
BRETON IS
MISSISSIPPI RIVER
MAIN PASS
PASS A LOUTRE
A
BAPTISTE COLLETTE SUBDELTA
NAUTICAL MILES
89°20'
89°10'
89°00'
29°30'
29°20'
29°10'
29°00'

FIG. 37.—Distribution of "*Rotalia*" *beccarii* (Linné) variants in per cent of total population. Per cent of fraction larger than 0.149 mm. without parentheses; per cent of fraction smaller than 0.149 mm. in parentheses.

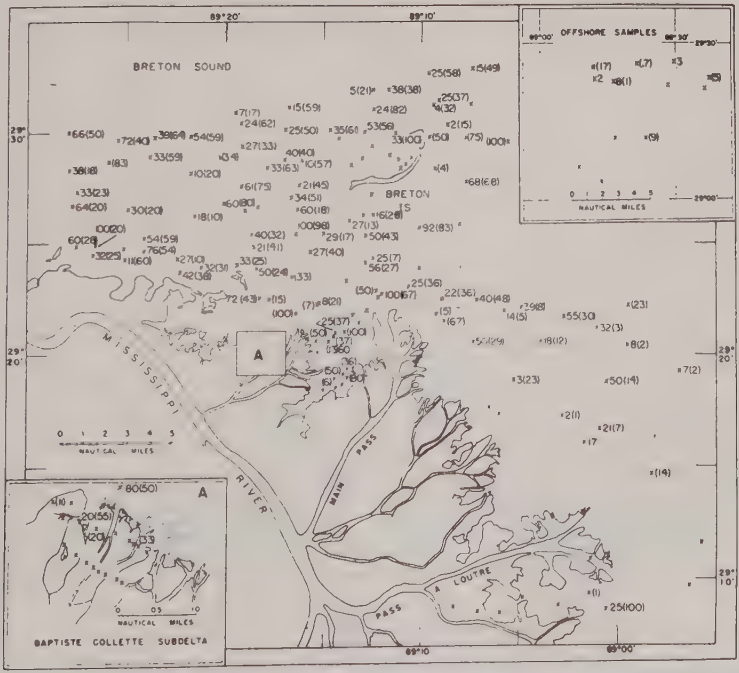

BRETON SOUND
OFFSHORE SAMPLES
BRETON IS
MISSISSIPPI RIVER
MAIN PASS
PASS A LOUTRE
A
BAPTISTE COLLETTE SUBDELTA
NAUTICAL MILES
89°20'
89°10'
89°00'
29°30'
29°20'
29°10'
29°00'

FIG. 38.—Distribution of "*Rotalia*" *beccarii* (Linné) variants in per cent of living population. Per cent of fraction larger than 0.149 mm. without parentheses; per cent of fraction smaller than 0.149 mm. in parentheses.

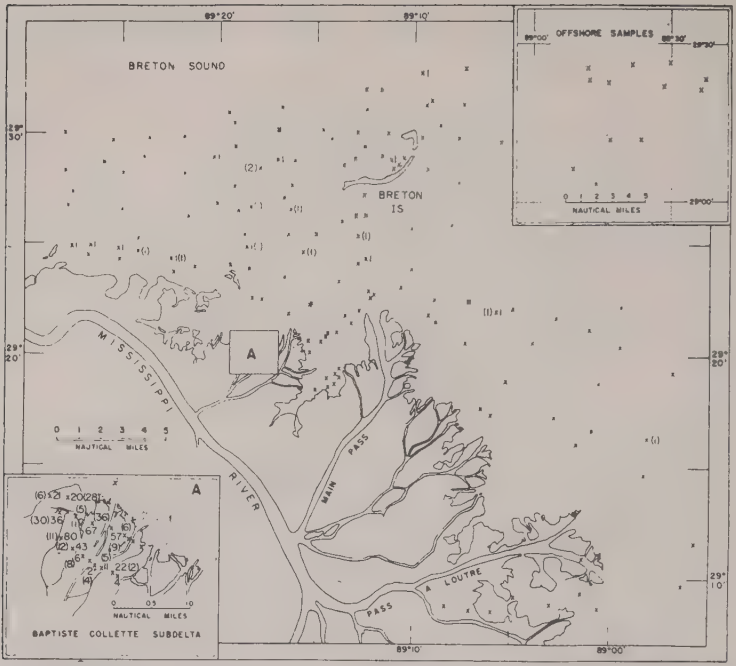

BRETON SOUND
OFFSHORE SAMPLES
BRETON IS
MISSISSIPPI RIVER
MAIN PASS
PASS A LOUTRE
A
BAPTISTE COLLETTE SUBDELTA
NAUTICAL MILES
89°20'
89°10'
89°00'
29°30'
29°20'
29°10'
29°00'

FIG. 39.—Distribution of *Trochammina macrescens* H. B. Brady in per cent of total population. Per cent of fraction larger than 0.149 mm. without parentheses; per cent of fraction smaller than 0.149 mm. in parentheses.

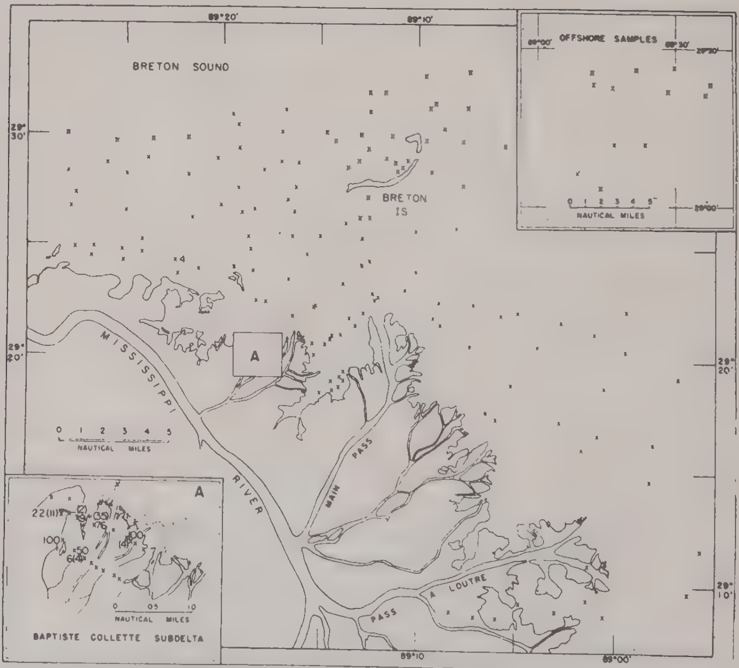

BRETON SOUND
OFFSHORE SAMPLES
BRETON IS
MISSISSIPPI RIVER
MAIN PASS
PASS A LOUTRE
A
BAPTISTE COLLETTE SUBDELTA
NAUTICAL MILES
89°20'
89°10'
89°00'
29°30'
29°20'
29°10'
29°00'

FIG. 40.—Distribution of *Trochammina macrescens* H. B. Brady in per cent of living population. Per cent of fraction larger than 0.149 mm. without parentheses; per cent of fraction smaller than 0.149 mm. in parentheses.

nearshore part of the open-gulf area, with average per cents of 10–25; local high ratio centers occur in Breton Sound. High per cent ratios (III) are seen on the northern side of the inlet between Breton Island and Main Pass and west of Main Pass, and in another nearshore area between Main Pass and Pass a Loutre. Areas showing great range in these per cents (IV) are in the marsh of Baptiste Collette Subdelta and the bay between Main Pass and Baptiste Collette Subdelta.

P. C. Scruton (ms.) has studied the depth changes as recorded on charts of this area covering the period 1860–1952. In general, his results show very rapid deposition at and near the present passes with a marked decrease offshore, an area of scour indicated at the position of the deepest part of the inlet north of Main Pass, and small and variable depth changes in the inner part of Breton Sound. The relative rates of sedimentation shown by the per cent of living Foraminifera coincide, in a general way, with what is known and can be inferred about sedimentation rates in this area. There is one exception: the high living frequencies on the northern side of the inlet do not agree with the information compiled by Scruton. This may be due to some local or short period variation in production caused by temporary conditions; it may also be due to very recent rapid sedimentation. The low relative sedimentation rate in the offshore samples s striking.

DISCUSSION

OCEANOGRAPHIC AND ECOLOGIC FACTORS

The principal feature of Foraminifera distribution in the southeastern delta area is the separation between the open-gulf fauna and the Breton Sound facies. It is rather surprising that there should be such a faunal discontinuity in an area where there are no great difference in depth of water and no striking geographic barriers. The wide inlets on both sides of Breton Island should permit unrestricted inflow of oceanic water if there are no other opposing forces.

It is believed that the distributions of the open-gulf species in this area reflect the distribution of the open-gulf water mass. Since these are benthonic species it appears reasonable to assume that their distributions are principally affected by the bottom water. The open-gulf water is more saline and dense than water from either the sound or from the distributaries of the Mississippi and tends to invade Breton Sound along the bottom as is demonstrated by vertical chlorinity distributions shown in Figures 1 and 2.

As the open-gulf bottom water enters the inlets on either side of Breton Island it becomes mixed with river water to produce Breton Sound water which is of intermediate chlorinities; also, there is mixing of open-gulf water with Breton Sound water. The shoaler depths inside the sound undoubtedly aid in this mixing so that the water column is essentially isohaline at many stations within the enclosed sound. The mixing of river and open-gulf water is clearly shown by the decreasing surface salinities as the mouth of a large distributary such as Main Pass is approached. Some of the water found in Breton Sound, however, probably comes from Chandeleur Sound which lies to the north and is not actually formed in the present area.

It has been pointed out above that a characteristic of this area is great variation in the salinity, and, to a lesser extent, temperature, from place to place and time to time. It is suggested, however, that distribution of the Foraminifera facies may represent an average distribution of the different water masses which condition their distributions. If this is true, the principal zone of mixing of water masses extends for 5–8 miles on either side of the inlets. The mixed faunas occurring in the bays and nearshore marshes represent the zone of water (and sediment) mixing, principally between the sound and the marsh water masses.

The open-gulf species which are restricted to the stations farthest offshore may be those adapted to the open-gulf water mass which is not affected by sound and river-marsh water. This subfacies thus may represent the landward extent of the uncontaminated shelf water mass. It is of interest to observe that species such as *Bigenerina irregularis* Phleger and Parker and *Cibicidina strattoni* (Applin) have their greatest abundance in this offshore facies; the same species are abundant much nearer the shoreline off the coast of Mississippi (Phleger, 1954). This suggests that undiluted open-gulf bottom water approaches nearer to the island barrier in the Mississippi Sound area than the same water does to Breton Sound.

There are some Foraminifera species occurring abundantly in both Breton Sound and the open gulf in the delta area which are largely confined to the open gulf in the Mississippi Sound area (Phleger, 1954). Examples of such species are "*Rotalia*" *beccarii* (Linné) variants and *Elphidium gunteri* Cole. The abundance of these species in Breton Sound suggests that the open-gulf water does occasionally invade along the bottom over wide areas within the sound. These species seem to be able to withstand considerable environmental variation once they have become established in an area. It is suggested that these species were introduced into Breton Sound with invasions of open-gulf water along the bottom. This may have been the result of physical transport of the very young, small forms of these species. Over a period of time, probably involving numerous invasions of nearshore gulf water, these species found the environment suitable and therefore flourished. Other species which may have been transported into the same area by the water invasions either could not survive or at least could not become abundant. It is of interest in this connection that most of the typically open-gulf species occurring in the sound are found only on the seaward side of the sound. This is the area where open-gulf water masses are expected to invade periodically. It seems likely that somewhat less frequent invasions of open-gulf water occur in the inner part of the area of Breton Sound which was examined. Such a mechanism may make the environment tolerable for these upper shelf species. Species such as "*Rotalia*" *beccarii* (Linné) variants and *Elphidium gunteri* Cole may be adjusted to less frequent invasions of open-gulf water.

The principal mechanism causing differentiation of sound and open-gulf facies undoubtedly is the abundance of fresh-water runoff from the Mississippi River drainage. Mixture of the river water with marine water at and near the inlets and distributary mouths constantly provides the intermediate water characterizing Breton Sound. The surplus of sound water is evidenced by the surface outflow of this water into the open gulf. An excess of this intermediate water tends to create a dynamic barrier and to keep the pure open-gulf water from invading Breton Sound. This is aided by two other factors: (1) the presence of Breton Island acting as a partial physical barrier and (2) the shallow depths within the sound which generally facilitate rapid wind mixing and destruction of open-gulf water characteristics. Open-gulf water does invade along the bottom at intervals, however, as already pointed out.

Comparison may be made between the distribution of facies of Foraminifera shown in Figure 10 and the distribution of sediments shown in Figure 4. There does not appear to be any obvious correlation between these two distributions, with the facies boundaries cutting across the sediment type boundaries. The same faunal facies is developed in several types of sediment; for example, the open-gulf, nearshore facies occurs in sediment which ranges from silty clay to sand. It is possible that there is some effect of sediment on the detailed distributions of these faunas, but analyses which have been made of all the species fail to demonstrate any correlation. It is hoped that future study may clarify this problem.

COMPARISONS WITH OTHER AREAS

It is of interest to compare the distributions in the present area with those of known faunas in other parts of the Gulf of Mexico, such as in the Mississippi Sound area (Phleger, 1954), and also the San Antonio Bay area (Parker *et al.*, 1953). Comparison between the two latter areas is discussed in the paper on the Mississippi Sound faunas.

The facies pattern in the present area is similar in general to that in the Mississippi Sound area. There are some distribution differences, however, which are of considerable importance. The boundary between the lagoon and open-gulf facies in Mississippi Sound is quite sharp. In the Mississippi Delta area, this boundary is in reality a transition zone extending over several miles. In Mississippi Sound the fauna is composed almost exclusively of species of *Ammobaculites;* calcareous species occur in the mixed faunas of the lower part of Mississippi Sound. Various calcareous species which are relatively widespread and abundant in Breton Sound are confined to the open gulf in the Mississippi Sound area. These calcareous forms in Breton Sound are various species of *Elphidium*, "*Rotalia*," *Nonionella*, *Bolivina*, and the Miliolidae.

These differences in distribution are believed to illustrate some important differences in the oceanography of the two areas. It appears that in the Mississippi Sound area the boundary between open-gulf and soundwater masses is consistently at approximately the position of the barrier islands. In Breton Sound, on the other hand, the faunas indicate great variability in the extent of open-gulf water along the bottom. The consistent position of the water-mass boundary in Mississippi Sound appears to be aided by the geographic barrier formed by the offshore islands. In the Breton Sound area such a barrier is only poorly developed in Breton Island. The fresh water runoff is large in both areas, but is larger and more variable in the Breton Sound area than in the Mississippi Sound area.

The Foraminifera distributions in the Mississippi Delta area are essentially similar to those in the San Antonio Bay area (Parker *et al.*, 1953). The oceanographic reasons for the distributions in these two areas, however, seem to be different. In the San Antonio Bay area the open-gulf water is introduced into the bays in quantity during times of low runoff and because of winds, tides, and extensive evaporation from the lagoon. During periods of high runoff a low-salinity water mass is formed in the lagoon, but in general the evaporation exceeds precipitation over the entire area much of the time. The principal general difference in the fauna of the two areas appears to be in the distributions of the marsh species. Marine marshes are very extensive in the Mississippi Delta area and are only of very limited extent in the San Antonio Bay area. This appears to reflect high runoff and thus rapid sedimentation in the Mississippi Delta area, and less rapid sedimentation in the San Antonio Bay area. As a result, the marsh faunas are more widespread in the Mississippi Delta area and also there is considerable natural contamination of marsh species into the bays and sound bordering the marsh. These latter specimens appear to be transported into the bays and sound from the numerous estuaries draining the marsh. There is also extensive natural contamination of the sound fauna with marsh species in Mississippi Sound from the extensive marsh bordering that area.

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THE SEASONAL OSCILLATION IN SEA LEVEL[1]

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ABSTRACT

On the basis of all available tide gauge records, bathythermograms, and Nansen bottle casts, we have compiled, on a global scale, monthly departures of *recorded* and *steric* sea levels from their annual means. The steric fluctuation is defined in terms of the seasonal fluctuation in specific volume. The results are given in the appendices and in three charts, together with error estimates. In general, the departures are comfortably above the uncertainties introduced by year to year variations and by the effects of local topography.

Recorded and steric departures agree remarkably well in low and temperate latitudes (conditions are *isostatic*). In these regions the steric levels are associated largely with temperature fluctuations in the upper 100 m. In high latitudes conditions are indeterminate.

Pronounced semiannual fluctuations are found along the west coast of South Africa, in Indonesia, in corresponding regions of the Labrador and Oyashio currents, and in the Gulf of Mexico and adjoining Gulf Stream stations (but not in the Kuroshio!). Elsewhere the oscillations are largely annual in character, with low sea level in each hemisphere during its spring and with high level during the fall. Recorded amplitudes vary from a few centimeters in the tropics to a few decimeters at higher latitudes; they exceed one meter in the Bay of Bengal. Atmospheric pressure effects and long period astronomic tides account for only a small part of the recorded fluctuations.

1. INTRODUCTION

The noteworthy compilation of 10^5 mean monthly heights of sea level from nearly all existing tide gauge stations, prepared by Proudman under the auspices of the Union Géodésique et Géophysique Internationale (UGGI, 1940, 1950), makes it possible to view the seasonal oscillation in sea level on a global scale. Numerous investigations have dealt with single stations or with small groups of stations.

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[1] Contribution from Scripps Institution of Oceanography, New Series No. 780. This compilation has been made possible by a grant-in-aid from the Institute of Geophysics, and by the support of the Office of Naval Research. We have also received substantial assistance from the Woods Hole Oceanographic Institution and the Hydrographic Office, U. S. Navy. We are especially indebted to Mrs. Jack Ludwick, Miss Evangeline P. Tollios, Mr. Gordon Groves and Mr. Heber Blair for their help.

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But it appears to be typical of meteorological and oceanographic phenomena that the larger the area under consideration the simpler they are. We believe, therefore, that an investigation on a global scale, although offhand more ambitious, is actually less so. It certainly is the more rewarding at this time.

For comparison we have also computed oscillations in the height of the sea surface arising from the seasonal variation in specific volume. These are called *steric* oscillations.[2] The steric sea level is high when the water is warm, low when it is cold. Conversely, a high steric level corresponds to a low value of salinity. The source of data consists of bathythermograms and, to a much lesser extent, Nansen bottle casts. For all oceans, information is now on file at the U. S. Navy Hydrographic Office for 5×10^5 bathythermograph casts and for 2×10^5 Nansen bottle casts. Although these numbers are impressive, the observations are so scattered in time and place that the seasonal changes in specific volume could be computed for only 69 areas, barely enough to indicate some global characteristics.

A comparison of recorded and steric fluctuations in sea level puts the problem on a much more definitive basis than would be possible with either set of data by itself. In some regions the two fluctuations resemble one another more closely (correlation 0.90 off Hawaii and Japan, 0.85 off Cape Hatteras) than any other sets of independent oceanographic observations known to us.

During the last few years some progress has been made in accounting for the mean ocean circulation in terms of the distribution of wind stress over the seas. The next problem is to account for departures from the mean circulation. This is much more difficult. The observed seasonal variations in sea level will have to provide much of the necessary empirical guidance for such an undertaking. We therefore present the following description even though we have not been able to explain it. A complete explanation probably involves the solution of most of the important unsolved problems in dynamic oceanography.

2. THE RECORDED SEA LEVEL

2.1 *Sources of tide gauge data.* The principal sources are the two publications prepared by Proudman and others (UGGI, 1940, 1950). Additional data were obtained from the U. S. Coast and Geodetic

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[2] The steric oscillations are nearly equal in magnitude to those in dynamic height, so that for traditional reasons the term *dynamic oscillations* would appear to be appropriate. But dynamic height has dimensions of work rather than length, and dynamic oscillation seems to us a poor adaptation of a poor term.

Survey, the Geographical Survey Institute of Japan (1950) and a few other sources. A footnote in Appendix I indicates if part or all of the data for a station are from a source other than the two UGGI publications. Some published stations were omitted because the data were too incomplete. Here it must be admitted that our standards were more exacting where more observations were available. For example, the Arctic and Antarctic stations were included in spite of the fact that the observations were scanty.

Appendix I lists the latitude and longitude of each station as given in the above references. The inclusive dates for the calendar years for which data are available are also given. When two calendar years represent data for 13 months or less, the inclusive months are indicated. The figure in parentheses following the dates indicates the number of years for which data are incomplete. The next column gives the total number of calendar years represented, except in cases where data for 13 months or less were available. This is considered as one year even though the observations may have extended through two calendar years. For example:

Years	*Total years*	
1931–39 (1)	9	Data from 1931 (incl) to 1939 (incl) but one year incomplete. Hence 9 years of data.
1935–41, 1943–46 (1)	11	Data from 1935 (incl) to 1941 (incl) and 1943 (incl) to 1946 (incl), with one year incomplete for latter period. Hence 11 years of data for both periods.
June 1941–May 1942 (2)	1	Data from June 1941 (incl) to May 1942 (incl), both years incomplete. Hence *one* total year by above rule.

2.2 *Normal monthly values.* The standard procedure is to take hourly readings of tide records. The published monthly value for, say January 1950, is a straight average of all hourly readings during January 1950. The figure appearing in the January column of Appendix I represents an average value for all Januaries for which sea level was reported at the particular station under consideration. Similar calculations of "normal monthly" values were made for all other months of the year. The mean value of the monthly means has been subtracted, so that the numbers in the appendix represent departures from an annual mean.

For stations with data for only part of a year among a group of stations with data for all 12 months, the reference level was adjusted so that the mean value of the available monthly means equalled the mean departure for the same months in the remaining stations of the group.

2.3 *Group averages.* The seasonal curve was drawn for each station. *Adjoining stations that showed similar behavior* were then combined into groups. Altogether there are:

419 stations
92 station groups
an average of 4.6 stations per group
an average of 20.6 years of record per station
longest record (133 years) is from Swinemunde, Germany.

The problem as to how individual stations should be combined to form group averages requires consideration. There are two obvious procedures. We could form an *average of stations*, assigning to each station equal weight; or we could form an *average of years*, lumping all data within the group together without regard to station. The former procedure would come close to giving us the geographic average we really want, except that the stations are never distributed too well throughout the area under consideration. The latter procedure leads to a minimum standard deviation in the group average.

The two procedures outlined above correspond to weighting each station average by

$$1 \text{ (or } n^0\text{)}\,, \qquad n \text{ (or } n^1\text{)} \tag{1}$$

respectively, where n is number of years of record. We have chosen a *root-weighted* average as a compromise.[3] Each station is weighted by the nearest integral number to

$$n^{\frac{1}{2}}\,. \tag{2}$$

In this way the group averages in Charts 1 to 3 and in Appendix I have been computed.

2.4 *Discussion of errors.* The monthly departures for each group (Charts 1–3) are estimates of normal seasonal conditions in the general area occupied by the stations in the group. In regions where the records are short and the stations few, there is doubt regarding the significance of secondary peaks or even of principal features. An estimate of the uncertainty of the plotted normal departures is therefore essential. It should be emphasized, of course, that the changes from year to year which give rise to this uncertainty are themselves of interest. But this is another story.

2.41 *Time variance.* The seasonal departures differ considerably from one year to the next, due largely to anomalies in weather (atmosphere and ocean). The fact that neighboring stations show similar anomalies in a given year eliminates observational error as an important factor. The compilation in Table I gives the standard deviation, ϵ, of a monthly departure from the annual average, taken year by year. The first line, for example, contains the standard deviation of the following 45 numbers: Göteborg, Jan. 1902 minus annual 1902, Jan. 1903 minus annual 1903, ..., Jan. 1946 minus annual 1946. In Table I we have selected stations with many years of record in both hemispheres and all major oceans, and, except in four instances, we have ignored the first ten years to give the station a chance to "settle down."

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[3] A better procedure is to use the "semiweighted" mean (Cochran, 1954), which Mr. Theodore Widrig called to our attention after the computations had been nearly completed.

TABLE I. STANDARD DEVIATION PER YEAR, ϵ, FOR STATED MONTHS

Group	*Station*	*Month*	*Years*	*n*	ϵ*(cm)*
3	Göteborg	Jan.	1902–46	45	11.6
3	Göteborg	Feb.	1902–46	45	10.9
3	Göteborg	April	1902–46	45	7.1
3	Göteborg	July	1902–46	45	5.2
3	Göteborg	Oct.	1902–46	45	11.1
21	La Plata*	April	1916–34	19	8.0
21	Buenos Aires	April	1915–46	31	6.3
21	Puerto de Colonia*	April	1938–46	9	8.2
21	Montevideo*	April	1938–46	9	6.2
21	Puerto de Punta del Este*	April	1938–45	8	9.3
8	Brest	April	1874–1943	70	6.2
30	Baltimore	April	1912–46	35	4.2
44	San Francisco	April	1907–46	40	5.2
49	Honolulu	April	1915–46	32	5.5
69	Hososima	April	1910–49	40	3.4
83	Bombay	April	1888–1946	59	4.3

* *All* years on record were used.

At Göteborg the standard deviation is small in spring and summer, large in fall and winter. For Group 21, which is a typical group according to the statistical summary in Section 2.3, the standard deviation for April varies from 6.2 at Montevideo to 9.3 at Puerto de Punta. Applying Bartlett's χ^2-test (Cochran, 1954), we obtain $\chi^2 = 35$ for Göteborg, and $\chi^2 = 2.9$ for Group 21, both with four degrees of freedom. The 5% significance level is at $\chi^2 = 9.5$. Thus the seasonal variation in ϵ at Göteborg is significant, whereas the variation between the different stations in Group 21 is probably not.

The mean April deviation for all stations in Table I is 6.15 cm.

A value of

$$\varepsilon = 6 \text{ cm} \tag{3}$$

will be taken as representative of the standard deviation of a monthly value for all months and all stations. The standard deviation of the normal monthly mean value based on n years of record is therefore

$$\varepsilon\, n^{-\frac{1}{2}} . \tag{4}$$

Since the annual variation in sea level has a double amplitude of the order of 20 cms, something like a decade of record is required to suppress the "noise level" at any one station to 10 per cent of the signal strength.

It can be verified that the standard deviation of the root-weighted group average is

$$\frac{1}{m^{\frac{1}{2}} < n^{\frac{1}{2}} >}\, \varepsilon = k\varepsilon , \tag{5}$$

where m is the number of stations comprising the group and where $< n^{\frac{1}{2}} >$ is the average value of $n^{\frac{1}{2}}$ for the m stations. Thus, for a group of four stations with records of 1, 4, 9, 16 years respectively, we have

$$k = \frac{1}{2\,(1 + 2 + 3 + 4)} = 0.2 .$$

2.42 *Geographic variance.* An additional uncertainty arises from the location of stations. Suppose that sea level varies erratically from bay to bay, from headland to headland. Then if each station in a group had been located one mile from its actual location, the resulting group average would have been different. Even if all records were exceedingly long so that the time-variance at each station was negligible, still there would be uncertainty as to the extent to which the computed group average is representative of the general area under consideration.

Two extreme cases are here considered. If departures at neighboring stations show no correlation, i.e., the departures are *incoherent*, then the total variance is the sum of the time variance and the geographic variance. If, however, the departures are *coherent* and the stations uniformly spaced, then the geographic variance does not contribute to the uncertainty of the group average. As an example of this latter case, consider a linear rise in sea level from station to station along a coastline. Then the station average gives the precise value for *average* sea level in the area. Shifting all the stations, or expanding the distance between them, would hardly affect the computed average. From the standpoint of variance the incoherent case may become the coherent case if the station spacing is sufficiently reduced.

The geographic variance has been estimated as follows. Let δ_i^2 be the mean square deviation of the 12 normal monthly values at the i^{th} station from the corresponding group averages. The root-weighted variance for all m stations in a group is

$$\delta^2 = \frac{\sum_{i=1}^{m} n_i^{\frac{1}{2}} \delta_i^2}{\sum_{i=1}^{m} n_i^{\frac{1}{2}}}.$$

This is taken as the geographic variance per station. The variance of the group average is then $m^{-1}\delta^2$.

In Appendix I the value of k precedes the uncorrected averages for each group, and $m^{-\frac{1}{2}}\delta$ (in cm) precedes the corrected averages. On Charts 1–3 the numbers following each group number give (in cm)

$$k\varepsilon \text{ and } \sqrt{k^2\,\varepsilon^2 + m^{-1}\,\delta^2} \text{ for } \varepsilon = 6.0 \text{ cm}. \tag{6}$$

These are low and high estimates of the standard deviation, corresponding (more or less) to coherent and incoherent groups of stations. But there are some difficulties inherent in this procedure, and it is not clear where the best estimate of variance lies.

As an example, consider the three neighboring groups

No.	*Locality*	*k*	*kε* *cm*	*m*$^{-\frac{1}{2}}$*δ* *cm*	*Limits of standard deviation* *cm*
7	North Sea (South)	0.04	0.24	0.40	0.2—0.4
8	English Channel	0.14	0.84	1.93	0.8—2.1
9	Bay of Biscay	0.36	2.16	2.11	2.2—3.0

The increasing irregularity of the curves toward the south, as seen on Chart 1, is related to the decrease in the number of observations.

2.43 *Suppression of the astronomic tides.* Short period astronomic tides are larger than the seasonal variation. However, the combination of hourly values into monthly averages for a given year and of corresponding values for several years into the "normal" monthly values suppresses the short astronomic tides. But the elimination is not complete. We shall consider briefly the extent to which spurious fluctuations in the mean monthly values can be attributed to the tidal residues.[4]

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[4] We are indebted for this method of treatment to Mr. Gordon Groves.

Let t designate time in mean solar hours and $y(t+1^h)$, $y(t+2^h)$, . . . $y(t+i^h)$, . . . $y(t+N^h)$ the tidal heights at $(t+1^h)$, $(t+2^h)$, . . . $(t+i^h)$, . . . $(t+N^h)$. This includes all hourly values from the first to last ($N'th$) hourly tidal height during the month.

For a pure harmonic constituent of speed σ(in hours^{-1}) and of unit amplitude,

$$y(t) = \cos(\sigma t - \eta)\,. \tag{7}$$

The monthly average is then

$$(1/N)\sum_{i=1}^{N} y(t+i) = f\cos(\sigma t - \eta + \tfrac{1}{2}\sigma N + \tfrac{1}{2}\sigma)\,, \tag{8}$$

where

$$f = N^{-1}\csc\tfrac{1}{2}\sigma\sin\tfrac{1}{2}\sigma N\,. \tag{9}$$

Table II gives the values of f for the principal tidal constituents for months of all possible lengths.

TABLE II. ATTENUATION FACTOR f

Constituent	*28 days*	*29 days*	*30 days*	*31 days*
M_2	.0019	.0006	−.0006	−.0016
S_2	.0000	.0000	.0000	.0000
N_2	−.0016	.0003	.0021	.0035
K_2	.0027	.0027	.0026	.0026
K_1	.0027	−.0027	.0027	−.0027
O_1	.0010	.0016	−.0040	.0060
P_1	−.0027	.0027	−.0027	.0027
Mf	.0242	.0564	.0837	.1050
MSf	−.0537	−.0183	.0156	.0466
Ssa	.9618	.9591	.9562	.9533
Sa	.9903	.9897	.9890	.9882

The contribution from any one semidiurnal or diurnal species is less than 1% of its amplitude. The total contribution depends on the actual amplitudes and relative phases. If all constituents are in phase in the monthly average, the total contribution to the monthly mean may reach as much as 1 cm at stations with extreme tides. On the average the contribution will be of the order of a millimeter.

The effect of the fortnightly tides is larger. The Mf constituent has an amplitude of the order of 5 cm, and the contribution to the monthly means will be of the order of several millimeters. At stations with large shallow water effects, the distortion of the primary constituents, M_2 and S_2, gives rise to a fortnightly constituent with the same period as the astronomic constituent MSf. Here the contribution to the monthly means may exceed a centimeter. The semiannual and annual constituents appear in the monthly averages with nearly, but not quite, their full amplitude.

The preceding discussion refers to any particular monthly mean in a single year. Consider now the contribution of the tidal constituents to an average over n years of this monthly mean. The arguments of the lunar constituents, M_2 N_2 O_1 Mf MSf, depend on the position of the moon, and their phase in any given monthly average will not vary in a simple manner from one year to the next. The cosine in equation (7) will take up in successive years scattered values between -1 and $+1$. Though the process is not random, strictly speaking, we might expect the lunar contribution to the monthly means to be of the order of $fn^{-\frac{1}{2}}$.

On the other hand, the solar constituents, K_2 K_1 P_1, have approximately the same argument at the beginning of a given month, regardless of the year, and the contribution to any monthly mean is given by equation (8) no matter how many years of record are averaged. The value must lie between $-f$ and $+f$, and if necessary it can be computed from the known values of σ, N, and η. There is a slight attenuation because the phase varies somewhat from year to year. We can compute an upper limit to the attenuation by considering K_2, whose argument shows the greatest variation (i.e., 40°; see Schureman, 1941: table 15), and by assuming that this argument at 0000 1 Jan. is with equal frequency at the extreme values of the 40° range. Then, since amp $\frac{1}{2}[\cos(x + 40°) + \cos x] = 0.94$, the reduction achieved by averaging over many years is only 6%. A slightly greater reduction is achieved for February because of the leap year variation in N.

The contribution from astronomic tides to the monthly means can be summarized as follows. For short records, say n less than 10 years, the principal factor is a nearly random contribution from fortnightly tides amounting to $0.1\ n^{-\frac{1}{2}}$ to $0.5\ n^{-\frac{1}{2}}$ cm. For longer records a nearly systematic contribution from solar constituents becomes predominant, and this is nearly independent of n. A typical value for K_1 is 0.1 cm. All these values are small compared to the observed standard deviation of about $6n^{-\frac{1}{2}}$ cm (Section 2.4_1), and it may be concluded that the present method of forming straight monthly averages is adequate. It should be pointed out, however, for the benefit of future oceanographers, that after a thousand years or so better methods for eliminating the solar constituents will become worthwhile.

3. THE STERIC SEA LEVEL

Wherever observations are adequate we have attempted to compute the seasonal departures in sea level arising from seasonal departures in specific volume. The resulting "steric sea levels," summarized in Appendix II, are shown in red on Chart 1. The selection and analysis of a large part of the observations have been made possible only by the help and active participation of the U. S. Navy Hydrographic Office and the Woods Hole Oceanographic Institution.

3.1 *Sources of data.* There are three sources of data:
(1) A few *analyses of seasonal variation* in temperature (and/or salinity) are available in journals and technical reports. They will be referred to under the author's name.
(2) *Bathythermograms* on file at Woods Hole and at Scripps Institution are referred to as WHOI and SIO.
(3) *Serial hydrographic observations* were provided by the Hydrographic Office, U. S. Navy (HYDRO).

Calculations have been made for 69 areas. The information given for each area in Appendix II is illustrated by the following examples:

No.	*Locality*	*Latitude*	*Longitude*	*BTs/Mo.*	*NB*	*Principal Source*
6	Off Gibraltar	32°–37° N	010°–015° W	104[1]	0[2]	WHOI
24	Aleutian Is.	52°–53° N	179° E–180°	8	1	Pattullo (1950)
3	North Sea	55°–60° N	005°–010° E	57[1]	unk.	Dietrich (1950)
55	Kuroshio[3]	unknown		unknown		Koenuma (1939)
		34°–35° N	139°–140° E	0	118	Japanese
		37°–38° N	142°–143° E	0	216	JAP-HYDRO

All observations for No. 6 were taken off Gibraltar between 32° and 37° N and 010° and 015° W. An average of 104 bathythermograms per month were available, but according to footnote 1 (App. II) some temperatures from reversing thermometers were included. The column under *NB* (Nansen bottle) indicates that no serial Nansen bottle observations were used. According to footnote 2, salinity was deduced from a *T-S* scatter diagram. Bathythermograms on file at the Woods Hole Oceanographic Institution are the principal source of data. In No. 24, the analysis was based on an average of 8 bathythermograms per month and 1 serial Nansen bottle cast. In No. 3 the principal source is an analysis by Dietrich based on an unknown number of Nansen bottle serial observations; however, some additional data consisting largely of bathythermograms have been used. No. 55 represents a special case. Here we have combined

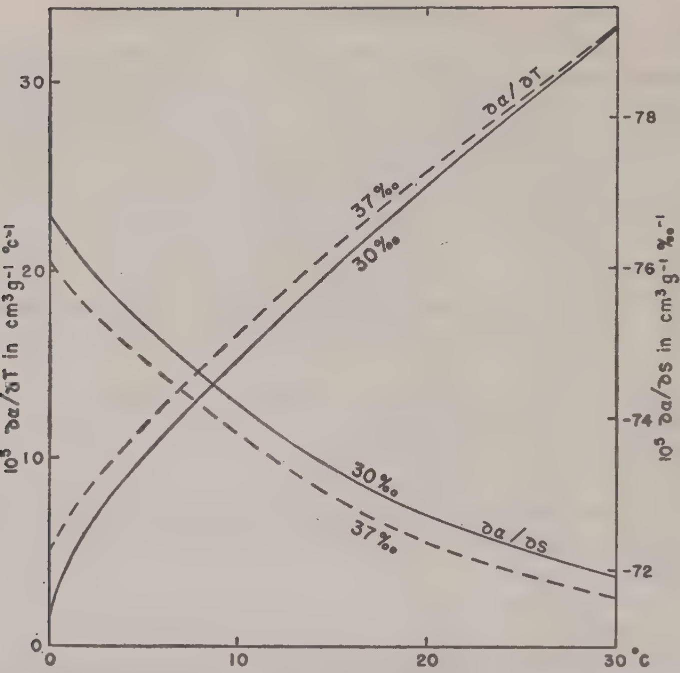

Figure 1. Thermal expansion, $\partial\alpha/\partial T$, and haline expansion, $\partial\alpha/\partial S$, of sea water at atmospheric pressure, as functions of temperature in °C for salinities $S = 30°/_{oo}$ and $37°/_{oo}$.

a temperature analysis by Koenuma with an assortment of Japanese serial observations.

3.2 *Thermal and haline effects.* From the available data we gain information concerning variations in the temperature and salinity fields with time of year at various depths (or pressures). For any depth let $\Delta T = T - \overline{T}$, $\Delta S = S - \bar{S}$ designate the monthly departures in temperature and salinity from their annual means, $\overline{T}$, $\bar{S}$. For small values of ΔT and ΔS the corresponding departure in specific volume is given by $\Delta\alpha = \alpha(T,S,p) - \alpha(\overline{T},\bar{S},p) = (\partial\alpha/\partial T)\Delta T + (\partial\alpha/\partial S)\Delta S + \ldots$, where $\partial\alpha/\partial T$ and $\partial\alpha/\partial S$ are to be evaluated at $\overline{T}$, $\bar{S}$, p. But the explicit dependence of $\partial\alpha/\partial T$, $\partial\alpha/\partial S$ on pressure can be neglected, and accordingly in all numerical work we have read $\partial\alpha/\partial T$ and $\partial\alpha/\partial S$ as functions of $\overline{T}(p)$, $\bar{S}(p)$, 0 (Fig. 1).

The "thermal" and "haline" departures are now defined by

$$z_T = g^{-1} \int_{p_a}^{p_0} (\partial\alpha/\partial T)\,\Delta T\, dp\,, \quad z_S = g^{-1} \int_{p_a}^{p_0} (\partial\alpha/\alpha S)\,\Delta S\, dp\,. \quad (10)$$

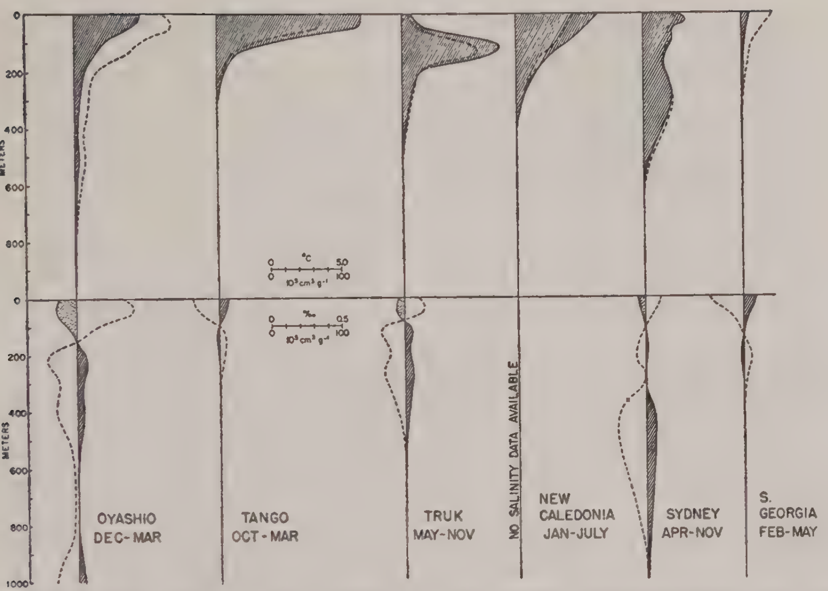

Figure 2. TOP. Ranges of temperature, ΔT, in °C (dashed lines, upper scale), and the resulting ranges of specific volume, $(\partial\alpha/\partial T)\Delta T$, in cm^3 g^{-1} (solid lines, lower scale) between months of maximum and minimum steric departures. BOTTOM. Ranges of salinity, ΔS, in ‰ (dashed lines, upper scale), and the resulting ranges of specific volume $(\partial\alpha/\partial S)\Delta S$, in cm^3 g^{-1} (solid lines, lower scale) between months of maximum and minimum steric departures.

The steric departures equal

$$z_s = g^{-1} \int_{p_a}^{p_0} \Delta\alpha \, dp \, . \tag{11}$$

Here p_a is the atmospheric pressure and p_0 the pressure to which the integration has been carried, presumably the pressure where all seasonal effects vanish.

3.21 *Thermal departures* have been computed for 69 localities. More than half of these are based on bathythermograph observations, which usually extend to only 450 feet (135 m). It was therefore necessary to augment the bathythermograph data by Nansen bottle temperature measurements and some subjective interpolation.

Fig. 2 shows some seasonal differences in ΔT and $(\partial\alpha/\partial T)\Delta T$. At most localities these quantities are large only in the upper few hundred meters or upper 10% of the sea. However, five southern hemisphere areas showed appreciable temperature variations as deep as 600 or 800 m. All of these were near the southern tips of the southern continents—Africa, South America, and Australia.

3.22 *Haline departures.* Only 30 areas were found with enough serial observations for computation of z_S. A third of these is in the western North Pacific; another third is south of Lat. 30° S. Only one satisfactory sample is from the cold Subarctic water of the northern hemisphere. This constitutes a far less satisfactory set of data than was available for z_T. It will be noted from Fig. 2 that ΔS usually changes sign with depth and that it extends deeper than ΔT.

3.23 *Steric departures* were computed in the usual way (LaFond, 1951) according to equation (11). Except for second and higher order terms they equal the sum of the thermal and haline departures.

3.3 *Discussion of errors.* It is difficult to give a rigorous discussion of errors when the original body of data has undergone subjective treatment. Nevertheless it seems desirable to make a rough estimate.

3.31 *Thermal errors.* Robinson (1951, 1952) has computed the standard deviation, s, of sea water temperatures from a normal monthly mean. Taking all available data, possibly from different years, which were collected during a specified month at a specified depth and location, she finds a value of 0.8°C to be representative of the upper 400 feet. Although we might expect that most of the variation takes place in this upper layer, let us assume this value to be representative all the way down to 400 m.

Suppose that this average is based on n' observations and that the deviations for any one bathythermogram are the same at all depths. Then the standard deviation of the mean temperature is $s(n')^{-\frac{1}{2}}$ and of the computed mean sea level departure $s\ (n')^{-\frac{1}{2}}\ (\partial\alpha/\partial T)\ h$. Typical numerical values are $s = 0.8°\ \mathrm{C}$, $n' = 25$ (the median for our data), $\partial\alpha/\partial T = 1.5 \times 10^{-4}\ \mathrm{cm}^3\ g^{-1}\ °C^{-1}$, and $h = 400$ m. The foregoing formula then gives the value 1.0 cm.

A second estimate has been made by computing z_T for each of 100 bathythermograms taken in August 1943–48 at Weather Station "Nan," 30° N, 140° W, No. 31. The standard deviation per year is $\varepsilon' = 2.9$ cm and per five-year average $2.9 \times 5^{-\frac{1}{2}} = 1.3$ cm. The value of ε' is roughly half of ε, the value adopted in Section 2.41 as representative of the standard deviation of the recorded departures.

For the three years 1943–46 the tide gauge and steric sea level records at Hawaii overlap (recorded group 49, steric group 35). For these three years we find $\varepsilon = 2.9$ cm, $\varepsilon' = 3.5$ cm. There is no evidence here for a difference between the standard deviations of recorded and thermal departures, but obviously the data are far from conclusive. The thermal departures appear smoother on Chart 1. This is due, at least in part, to the fact that they were computed from smoothed temperature data, whereas the recorded departures are drawn through each point without smoothing.

There are also systematic errors. Neglect of the direct pressure effect on $\partial\alpha/\partial T$ leads to a computed amplitude about 5% too small. Furthermore, we have neglected second and higher order terms. The ratio of these to the first order terms is of the order

$$\frac{(\partial^2\alpha/\partial T^2)\,(\Delta T)^2}{(\partial\alpha/\partial T)\,\Delta T} = \frac{(\partial^2\alpha/\partial T^2)\,\Delta T}{\partial\alpha/\partial T} = \frac{(10^{-5}\mathrm{cm}^3\,g^{-1}\,{}^\circ\mathrm{C}^{-2})\,(1\,{}^\circ\mathrm{C})}{1.5 \times 10^{-4}\mathrm{cm}^3\,g^{-1}\,{}^\circ\mathrm{C}^{-1}} = \frac{1}{15}\,.$$

This will make the computed sea levels too low in both extreme seasons but it will leave the ranges almost unaffected.

3.32 *Haline errors.* We have not been able to find a study of salinity variability that is comparable to Mrs. Robinson's work on temperature. Our data, though not rigorously analyzed by statistical methods, suggest a value of about 0.10‰ for the standard deviation. On an average there are eight observations per month, and our estimate of the error following Section 3.31 is then 2 cm. But now there are additional uncertainties associated with the fact that the contributions from some depths cancel those from other depths (Fig. 2), so that the final value represents a difference of two uncertain quantities. Only at stations with rather large haline departures can the computed values of z_S be considered significant.

Systematic errors in haline departure are quite small. The effect of pressure on $\partial\alpha/\partial S$ again leads to a computed amplitude that is too small, but by less than 2%. The ratio of the second order to the first order term is less than 0.001.

4. ATMOSPHERIC PRESSURE

The last three lines for each group of stations in Appendix I give a correction for the isostatic yielding of the ocean surface to the fluctuating atmospheric pressure. On first consideration, the only requirement seems to be that the sea surface be depressed by 1 cm for every rise in pressure[5] by 1 mb in the general area of the group of tide stations. This has been done in previous investigations. But this procedure does not take into account a surprisingly large annual change in the mean pressure over all oceans, from 1012 mb in December to 1014 mb in July, due principally to a shift in air mass toward Siberia in winter. It is clear that no correction would be required if the annual change in pressure were uniform over all oceans.

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[5] The pressure exerted by 1 cm of sea water is 1.005 mb.

Let P_g designate the mean monthly pressure in the general vicinity of the group of tide gauge stations and P_0 the mean pressure over all oceans for the same month (Table III). Then $c' = P_g - P_0$ represents the amount by which the water surface in this area is depressed relative to mean global sea level. The recorded sea level has to be raised by this amount to correct for the effect of atmospheric pressure. Since the base level is arbitrary, it is more convenient to use the correction factor $c = c' - \overline{c'}$, whose mean annual value is zero. These four steps are illustrated in Table III. In Appendix I the last four lines for each station group designate z, $P_g - 1000$ *mb*, c, and $z + c$. The quantities z, c, and $z + c$ have a zero annual mean. The second line in Table III designates the mean pressure over all oceans, and of course it is the same for all tide groups. The average was formed on the basis of values for each 5° quadrangle between 90° N and 10° N (U. S. Department of Commerce, 1946) and for each 10° quadrangle between 10° N and 60° S (Bartholomew and Herbertson, 1899). These two references were also the source of the P_g values.

TABLE III. EXAMPLE OF PRESSURE CORRECTION

	J	*F*	*M*	*A*	*M*	*J*	*J*	*A*	*S*	*O*	*N*	*D*
P_g – 1000 mb	6.5	8.0	9.0	9.5	14.5	14.0	11.5	10.0	10.5	8.5	7.0	7.0
P_0 – 1000 mb	12.4	12.4	12.8	12.8	12.8	13.5	14.0	13.3	13.4	12.8	12.6	11.9
$P_g - P_0$	–5.9	–4.4	–3.8	–3.3	1.7	0.5	–2.5	–3.3	–2.9	–4.3	–5.6	–4.9
c (cm)	–2.7	–1.2	–0.6	–0.1	4.9	3.7	0.7	–0.1	0.3	–1.1	–2.4	–1.7

The foregoing isostatic adjustment for atmospheric pressure changes would be invalid for quick changes in pressure. There simply would not be time for the water to move. Various theoretical models yield time constants short compared to a year. Empirical evidence (to be published shortly by Mr. Gordon Groves) indicates that sea level yields virtually isostatically to atmospheric pressure disturbances with dimensions of several thousand miles and a time scale of several days. We are satisfied that the isostatic adjustment to atmospheric pressure is a suitable approximation for the annual term.

We have made no allowance for wind stress. Changes in wind accompany changes in pressure, and the wind effect is likely to be larger and opposite in sign to the pressure effect. This may account for the fact that in some cases the variation in sea level, corrected for atmospheric pressure, is actually larger than the uncorrected variation (see Section 6.6).

5. LONG PERIOD ASTRONOMIC TIDES

In this section we consider the extent to which astronomic tides of annual and semiannual period contribute to the recorded monthly departures. Rayleigh has shown (Lamb, 1932) that tides in the actual oceans[6] with periods long compared to a day have nearly the values given by the equilibrium theory. For the solar annual (Sa) and the solar semiannual (Ssa) species, these values are (Doodson and Warburg,[7] 1941)

$$z = [0.16 \cos(\odot - 282^\circ) + 0.98 \cos 2\odot]\,(1 - 3 \sin^2 \phi)\,, \quad (12)$$

where ϕ is latitude and $\odot$ the sun's longitude (March 21: $\odot = 0, 2\pi$; June 21: $\odot = \frac{1}{2}\pi$, etc.).

The above formula must be corrected for the elastic yielding of the crust (relative to which sea level is measured) and for the gravitational attraction of the tidal bulge on itself by multiplying by a factor (Jeffreys, 1952: 204)

$$1 + k - h = 0.69\,, \quad (13)$$

where k and h are "Love's numbers."[8] In addition, we must superpose a uniform tide z' over all oceans so that the total tidal volume

$$\int_{ocean} z\,(\odot, \phi)\, d\sigma + z'\,(\odot) \int_{ocean} d\sigma$$

vanishes in spite of the irregular distribution of land and sea. When this is done, the expression $(1 - 3 \sin^2 \phi)$ in equation (12) is replaced by

$$3(1 - D/C) - 3 \sin^2 \phi = 0.91 - 3 \sin^2 \phi\,, \quad (14)$$

where $C = \iint \cos \phi\, d\phi d\theta = 8.79$ and $D = \iint \cos^3 \phi\, d\phi d\theta = 6.11$ are integrals over such ranges of latitude ϕ and longitude θ as are covered by oceans. The values were obtained by Munk and Revelle (1952: 333) by numerical integration.

Applying these two factors to the above formula for the equilibrium tide gives

$$z = [0.11 \cos(\odot - 282^\circ) + 0.68 \cos 2\odot]\;(0.91 - 3 \sin^2 \phi)\,. \quad (15)$$

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[6] In the case of an ocean covering the entire globe, this result probably does not hold (Lamb, 1932: 362; Jeffreys, 1952: 371).

[7] The numerical results follow from equations (4.3a for sun), (4.3b), (7.10a), and Table 7.17, setting $p = 282^\circ$ and writing $\odot$ for h.

[8] This k is used in accordance with convention. It is not the k used in other sections of this paper.

An observational test of this formula is impossible because the meteorological effects of annual and semiannual period far outweigh the astronomic effects. The only long period tide for which the astronomic factors predominate is the lunar fortnightly tide, and here at least an expression analogous to (15) agrees roughly with the results of observations. Fig. 3 shows the height of the combined annual and semiannual tides according to equation (15). The maximum tidal range is 3.2 cm between March 20 and June 21 at latitude 90°. This value is much smaller than a typical value for the recorded range.

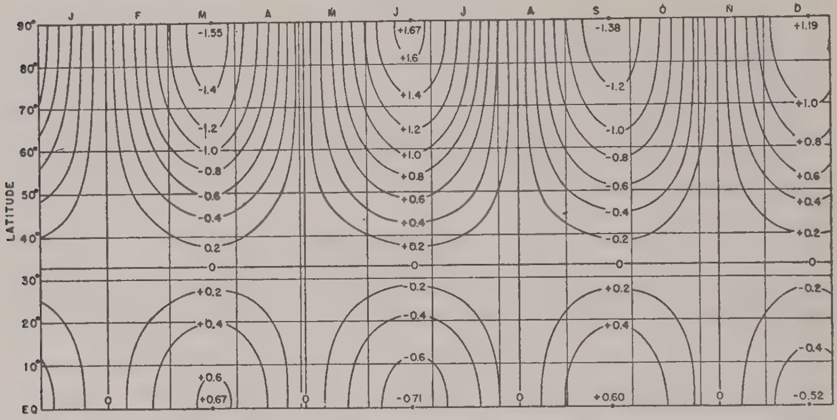

Figure 3. Long period tides in centimeters as a function of latitude and month.

6. DISCUSSION

This is a presentation of data so combined and so plotted as to give a global summary of seasonal oscillation in sea level. No hypothesis is offered as to the causes of the observed oscillation.

6.1 *The data.* The geographic distribution of stations gives a remarkably good picture of the geographic extent of western civilization, but it is hardly a desirable distribution from our point of view (see Chart 1). More than one third of the stations are around the shores of northern Europe and the British Isles. Some 72% of the tide gauge groups, 75% of the steric height summaries, 79% of the tide stations, and 92% of the tide station-years are from the northern hemisphere. Most of the sea level observations refer to shores of larger land masses. Sea level data in midocean are available for five island groups in the Atlantic and for ten islands in the Pacific. Vast areas of the North Atlantic and Pacific are without any midocean observations whatsoever, and one must beware lest the aversion of coral for cold water become the basis of a hypothesis for seasonal changes in sea level.

Comparison of the recorded and steric sea level observations is made difficult by the fact that these are for the most part neither synchronous nor adjacent. Moreover, different methods of averaging had to be used for these two kinds of observations; the steric departures show the result of smoothing whereas the recorded departures do not.

In this kind of study, questions concerning the reliability, even the reality, of the results are paramount. We have attempted to estimate the standard errors of the results obtained.

6.2 *Description of recorded sea levels.* The seasonal range varies from a few centimeters at several island stations in low latitude to 165 cm in the Bay of Bengal. Large seasonal changes are found in the monsoon regions of the western Pacific and Indian Ocean, in the Red Sea and the Persian Gulf, the west coast of Mexico and Central America, the North Atlantic north of 60°, the Gulf of Alaska, and the Sea of Japan. In general, amplitudes are smaller in the southern than in the northern hemisphere.

Fig. 4 is a synopsis of North Atlantic and North Pacific observations. Two zones of high annual activity correspond quite well to the subtropical and subpolar gyres of ocean circulation (Munk, 1950). In either zone the double-amplitude reaches close to a foot. In the subtropical zone, the high is in September, the low in March; in the subpolar zone the extremes occur three months later. There is an indication of an oscillation in the equatorial gyre which is roughly in phase with the subtropical gyre though only half as large.

Sea level in both hemispheres is generally low in their respective spring seasons and high in the fall. An exception occurs at the Great Australian Bight, where sea level is highest during the southern winter and lowest in summer. The boundary between the northern and southern types does not always follow the geographic equator; it lies north of it in the western Pacific and western Indian Ocean. The intrusion of the southern type into the Gulf of Siam is particularly striking (Chart 3).

In most regions the oscillation is annual in character. Pronounced semiannual oscillations in sea level occur off the west coast of India, in Indonesia, off the west coast of Africa, in the Labrador Current region of the western North Atlantic and the corresponding Oyashio region of the western North Pacific, and in the Gulf of Mexico and adjoining Gulf Stream stations (but not in the corresponding region of the Kuroshio!). A few curves on Chart 1 have even shorter period oscillations, but their reality is doubtful.

6.3 *Marginal seas.* In the Baltic (Chart 2), the Mediterranean, the North Sea, Hudson Bay, the Gulf of California, and the Sea of Japan, the annual variation in sea level corresponds closely to that

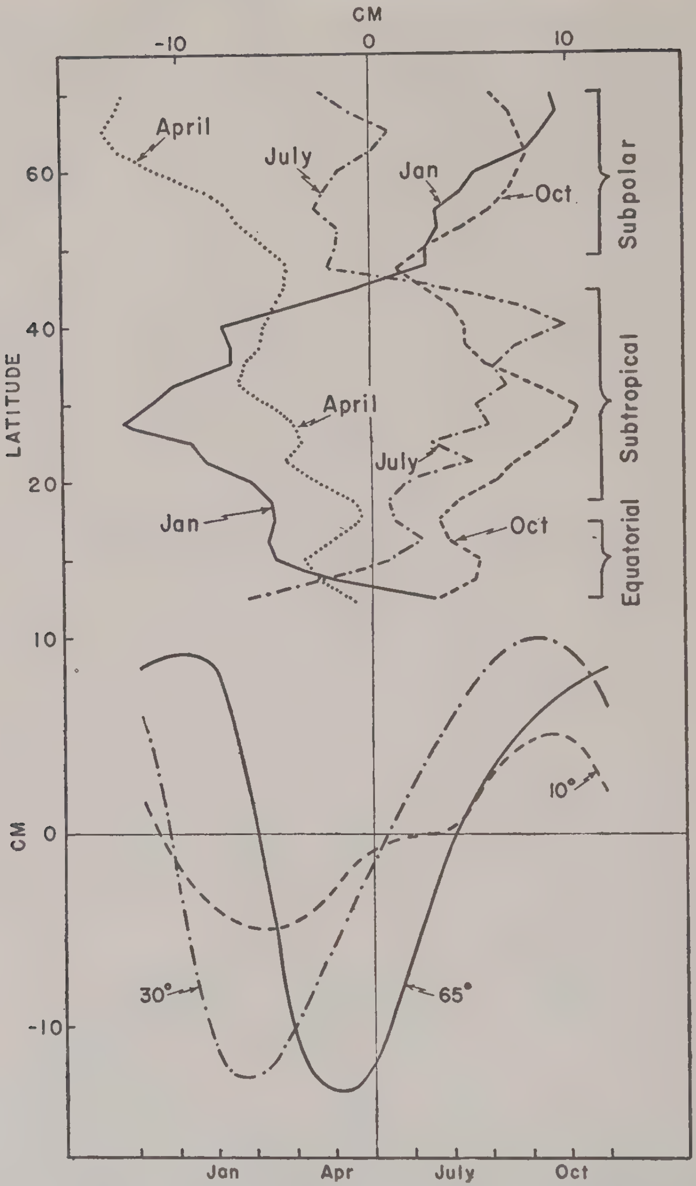

Figure 4. UPPER. Recorded departures from mean sea level as a function of latitude for each of four months. LOWER. Average recorded departures from mean sea level as a function of month. Each curve represents a ten-degree belt of latitude.

(466)

in the adjacent oceans at about the same latitude. Seasonal departures throughout these complex inland bodies of water are remarkably uniform. In the Red Sea the times of maximum and minimum sea level are similar to those in the western Indian Ocean, but the range is greater. The Persian Gulf is unlike any other region, and there are many complexities in the East Indies, corresponding to the complex topography and current systems of this region (see Chart 3). Striking double maxima in the Gulf of Mexico have already been referred to. Data for the Arctic Sea are completely inadequate.

6.4 *Description of steric sea levels.* The steric level is nearly equal to the algebraic sum of the thermal and haline departures. These two kinds of departures have quite different characteristics.

The average range of thermal departures is 11 cm. Maximum ranges of 25 cm are observed in the Sea of Japan and north of Bermuda. Small thermal departures are observed in some equatorial and most polar regions.

The haline departures do not tend to cluster around a mean value. Two-thirds of the z_S computations yield virtually negligible ranges—5 cm or less. The haline departures are consistently small around Bermuda and in the vast oceanic area east and southeast of Japan. Appreciable values of z_S occur: (a) at one location in the Bay of Bengal (a range of 41 cm); (b) at the five southern hemisphere localities that show deep thermal variations; and (c) along the continental slope off eastern Asia, from Formosa to Hokkaido.

On the whole, steric departures are in phase with recorded departures. In equatorial latitudes the steric departures are largely thermal and relatively small. The considerable irregularity from place to place prevents one from making any easy generalization, but recorded and steric departures may not be far out of line here.

In subtropical latitudes the steric departures are mostly thermal and quite large. On the average they agree well with the recorded departures.

In subpolar latitudes the thermal departures are small and the recorded departures large. Unfortunately the rôle of salinity remains in doubt. Where salinity observations are available, the water is shallow. Deep salinities are available for only the Oyashio (steric No. 58), which has abnormally small recorded departures. But there, at least, the haline departures are equivalent to the thermal departures, and together they lead to a fair agreement between steric and recorded departures. This suggests that in subpolar latitudes as well there may be agreement between recorded and steric departures. In order for this to be true there must be large and deep seasonal changes in salinity of the required amount, and as a consequence the haline departures must be large compared to the thermal departures. Observations will tell.

6.5 *Astronomic tides.* Comparison of Fig. 3 with Chart 1 shows that at all latitudes the long period astronomic tides are much smaller than the recorded departures in sea level.

6.6 *Atmospheric pressure effects.* In general, changes in atmospheric pressure exert an effect which is small compared with the observed departures in sea level. In most cases the effect of "correcting" for pressure is a small reduction in range; the average reduction for all stations is 1.6 cm. The groups where the pressure correction is most prominent are illustrated in Fig. 5. Column 1 contains all groups where the pressure correction *decreases* the range by more than 10 cm. All but one of these groups are in the seas surrounding Japan. Group 36 is off southern Greenland, near the center of the Icelandic low. Column 2 contains all cases where the range is *increased* appreciably. These groups are generally of southern hemisphere type, although a few are actually north of the equator. They occur off the southeast coasts of Africa, Australia, and New Zealand. The anomalous member of this set, No. 61, is located in the East China Sea. Column 3 illustrates stations where the phase is changed. Most of these have either rather small amplitudes or multiple maxima and minima, and the change of phase occurs when one of these extrema is accentuated by the correction. This class lacks geographical coherence.

6.7 *Isostasy.* In many regions the recorded departures nearly equal the steric departures plus the departures in atmospheric pressure. In such regions the total weight of water and air per unit area tends to remain nearly constant throughout the year, so that a pressure recorder at the sea bottom would show very small seasonal fluctuations. In analogy with geologic usage, this condition will be called *isostatic.* For oceanographic usage we suggest, as a strict definition, that conditions be called isostatic if the *hydrostatic* pressure due to atmosphere and ocean at a point on the deep sea floor does not change with time. Under such isostatic conditions the *measured* pressure at this point would remain nearly constant, varying only in response to accelerations in the fluid motion. Astronomic tides give rise to small departures from isostasy both because of changes in g and in water mass per unit area. In an isostatic region, surfaces of constant pressure coincide at depth with surfaces of constant gravitational potential.

(468)

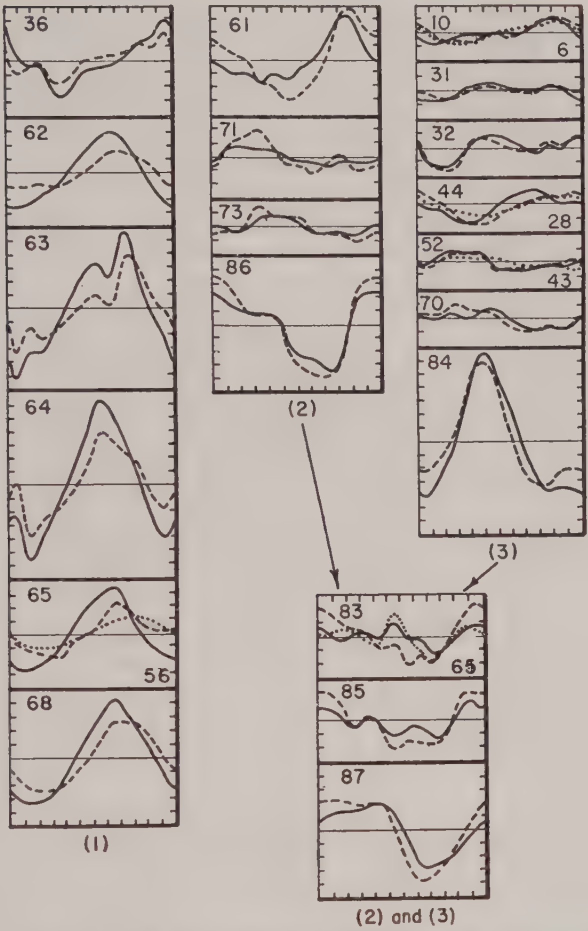

Figure 5. Groups for which the atmospheric pressure effect is most pronounced. Solid curves are recorded levels; dashed curves are the levels "corrected" for atmospheric pressure; dotted curves are steric levels. Column (1) includes all cases where the pressure correction decreases the range by more than 10 cm; column (2) where it increases the range by more than 5 cm; and column (3) where the time of maximum or minimum is changed by three months or more. Groups 83, 85 and 87 belong to both columns (2) and (3).

Nomitsu and Okamoto (1927) noted the close correspondence between recorded and steric levels off Japan, and LaFond (1939) demonstrated a similar correspondence off southern California, but the widespread occurrence of quasi-isostatic conditions emerges as a primary result of the present study.

Since the effects of atmospheric pressure are usually small, the latitude dependence of isostasy can be inferred from Section 6.4. Outstanding examples of isostasy are found near the Azores, Bermuda, Hawaii, off California, along the coasts of Japan and even in the high annual tide of the Bay of Bengal. In some of these cases the atmospheric pressure correction enters as an important factor (Fig. 5).

There are a number of regions where, for one reason or another, the situation is indeterminate. For example, in the area of the Florida Current the recorded levels are from the western side while the steric (thermal) levels are from the eastern side of the stream; the shallow depth along the western side does not permit the calculation of steric levels. A similar situation exists off Nova Scotia and off the west coast of Florida. The degree of isostatic adjustment in the southern hemisphere cannot be determined from the available data, but there is no evidence against isostatic adjustment at low latitudes; possibly there is an indication of isostasy as far south as 60° S, off the Palmer Peninsula (recorded level group 90 and steric level group 69).

In spite of quite a number of thermal calculations, little can be said about isostasy in the Arctic and Subarctic waters of the northern hemisphere. The thermal departures alone are definitely neither large enough nor of the right phase for isostasy. The only Subarctic locality *in deep water* with salinities as well as temperatures, off Hokkaido, exhibits isostasy effected by deep changes in salinity. Other cold-water localities (Korea, Norwegian Sea, Barents Sea, etc.) are on the continental shelves, where deep-level compensation is impossible.

6.8 *Relative and absolute currents.* It is emphasized in oceanographic textbooks that the standard computation of currents from dynamic topography can yield only relative values. Yet, in the few instances where comparison with actual current measurements have been made, the relative and absolute currents have agreed rather well. There is harmony between these findings and the widespread occurrence of isostatic conditions. For in isostatic regions, *seasonal changes* in absolute current can be determined from measurements of dynamic height. Our study can give no evidence concerning the mean conditions.

6.9 *The International Geophysical Year.* The principal shortcomings of the present data could be overcome by making synchronous and adjacent observations of recorded and steric levels, with emphasis on (1) island stations near deep water in the southern hemisphere, and (2) Subarctic waters, where recorded departures are large and thermal departures are not. A single year's observations should be sufficient to clarify many of the uncertainties that now remain. It is hoped that this might be accomplished during the forthcoming International Geophysical Year.

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As this paper went to press our attention was directed to a recent study by Eugénie Lisitzin, Les Variations Annuelles du Niveau des Océans, Bulletin d'Information, Comité Central d'Océanographie et d'Études des Côtes, No. 6, June 1955. Dr. Lisitzin studied the annual term on the basis of 140 selected stations distributed over all oceans. She has noted the phase reversal between northern and southern hemispheres as well as the three months phase lag in the subpolar regions relative to the subtropical regions. We pointed out this feature for the northern hemisphere only, but Dr. Lisitzin has found evidence for this in the southern hemisphere as well.

APPENDIX I

1. ATLANTIC (ARCTIC SECTOR): Barents Sea

Station	Latitude	Longitude	Years	Total Years	J	F	M	A	M	J	J	A	S	O	N	D
Liinahamari (Fi)	69°39N	31°22E	1931–39(1)	9	7.5	4.0	−7.4	−12.1	−13.0	−5.4	−4.5	−1.5	4.8	8.8	9.7	8.8
Vardö (No)	70°22N	31°06E	1880–85(3)	6	14.8	5.8	−6.4	−18.9	−15.7	−7.1	−1.2	1.2	0.3	3.0	11.9	11.7
Berlevåg (No)	70°51N	29°06E	1939–41(1), 1942–43(1)	5	5.9	7.3	−7.5	−5.5	−11.8	−6.1	−7.7	−3.5	3.2	5.0	7.7	13.2
				k = .22	9.1	5.5	−7.1	−12.2	−13.4	−6.1	−4.5	−1.3	3.1	6.1	9.8	10.9
				P_g	8.0	6.5	8.0	11.0	14.0	12.5	12.0	11.0	9.5	8.0	6.5	8.0
				c	−1.1	−2.6	−1.5	1.5	4.5	2.3	1.3	1.0	−0.6	−1.5	−2.8	−0.6
				±1.39	8.0	2.9	−8.6	−10.7	−8.9	−3.8	−3.2	−0.3	2.5	4.6	7.0	10.3

2. ATLANTIC: Norway, West

Station	Latitude	Longitude	Years	Total Years	J	F	M	A	M	J	J	A	S	O	N	D
Andenes (No)	69°19N	16°09E	1938–46(3)	9	6.4	5.2	−2.6	−6.9	−14.5	−8.4	−12.6	−3.0	1.9	9.6	11.0	13.7
Narvik (No)	68°26N	17°25E	1928–39(3)	12	8.7	−1.6	−6.0	−16.8	−14.1	−6.2	0.5	−2.6	1.2	10.9	14.9	11.6
Kabelvaag (No)	68°13N	14°30E	1880–85(3)	6	13.5	8.5	−7.3	−14.1	−6.0	−8.6	−4.2	−3.4	−3.8	2.0	9.3	14.5
Trondhjen (No)	63°26N	10°22E	1872–74(3), 1877–78 (2), 1880–81(2)	7	18.9	1.8	−10.1	−16.5	−7.7	−3.3	−5.9	−9.8	−3.9	9.0	15.8	11.3
Heimsjöen (No)	63°26N	9°07E	1935–41, 1943–46(1)	11	8.6	5.1	−8.0	−8.1	−15.1	−5.1	−6.1	−1.7	2.9	11.1	3.6	12.3
Kjöllesdal (No)	61°55N	5°38E	1935–41(2), 1943(1), 1945–46(1)	10	4.3	−0.5	−7.6	−9.2	−14.9	−4.8	−0.9	0.3	5.0	9.6	11.1	7.6
Bergen (No)	60°24N	5°18E	1883–89(2), 1928–40, 1944(1), 1946	22	8.4	−1.3	−7.1	−13.9	−13.8	−6.9	−0.7	1.8	2.5	11.0	11.6	8.8
Stavanger (No)	58°58N	5°44E	1881–85(5), 1928–39(1)	17	4.4	−4.2	−8.5	−9.3	−13.2	−2.6	0.1	3.3	2.1	9.8	15.3	2.6
				k = .10	8.7	0.9	−7.2	−11.8	−12.8	−5.6	−3.3	−1.3	1.4	9.6	11.8	9.7
				P_g	6.5	8.0	9.0	9.5	14.5	14.0	11.5	10.0	10.5	8.5	7.0	7.0
				c	−2.7	−1.2	−0.6	−0.1	4.9	3.7	0.7	−0.1	0.3	−1.1	−2.4	−1.7
				±1.13	6.0	−0.3	−7.8	−11.9	−7.9	−1.9	−2.6	−1.4	1.7	8.5	9.4	8.0

3. ATLANTIC: Skagerrak, Kattegat, and Eastern North Sea

Tregde (No)	58°00N	7°34E	1935–40, 1942–43(1), 1945–46	10	1.5	1.0	−8.5	−6.4	−8.5	−4.1	0.2	1.6	5.3	6.1	8.1	4.2
Nevlunghavn (No)	58°58N	9°53E	1935–41(2), 1943–46	11	−0.6	−1.3	−9.9	−8.9	−11.0	0.7	4.7	5.0	6.1	4.5	9.1	1.9
Oscarsborg (No)	59°41N	10°37E	1872–82(4)	11	−5.0	−13.0	−15.6	−15.2	−9.5	2.7	10.7	13.7	15.4	8.6	5.5	2.0
Oslo (No)	59°54N	10°45E	1885–90(1), 1928–46(1)	25	−0.1	−8.5	−11.3	−12.6	−11.9	0.8	8.3	9.0	7.7	10.0	6.9	1.2
Strömstad (Sw)	58°57N	11°11E	1900–23, 1925–40, 1946(1)	41	1.4	−4.3	−10.5	−10.6	−8.4	−0.2	4.9	7.5	4.5	4.0	6.7	4.7
Smögen (Sw)	58°22N	11°13E	1911–46	36	5.0	−2.8	−5.1	−6.4	−5.0	−2.1	1.1	2.6	2.1	3.6	2.9	3.9
Bäckevik (Sw)	58°22N	11°15E	1895–1928	34	1.8	−2.8	−9.5	−10.8	−8.0	−1.6	4.1	7.2	5.4	4.0	5.6	4.9
Göteborg (Sw)	57°43N	11°57E	1887–1900, 1902–46	59	0.6	−3.8	−9.3	−11.5	−9.4	−1.6	4.6	8.2	6.8	6.0	5.6	4.0
Varberg (Sw)	57°06N	12°13E	1887–1946	60	0.0	−4.3	−9.5	−10.4	−9.6	−1.6	4.7	8.2	7.1	6.7	5.1	3.6
Frederikshavn (De)	57°26N	10°34E	1893–1946(1)	54	1.7	−3.5	−9.6	−9.5	−10.4	−1.4	4.0	6.1	5.1	5.7	6.8	5.1
Hirtshals (De)	57°36N	9°57E	1892–1946(4)	55	1.2	−3.6	−10.7	−9.9	−11.0	−0.8	5.3	7.4	6.1	6.5	5.0	4.3
Esbjerg (De)	55°28N	8°27E	1889–1946(1)	58	5.2	−2.6	−10.7	−13.9	−16.1	−7.0	0.7	6.4	6.5	10.5	10.8	10.8
Bremerhaven (Ge)	53°34N	8°34E	1898–1943	46	−0.2	−4.5	−9.9	−6.5	−9.1	−0.2	4.4	6.7	5.1	5.1	5.1	3.4
				k = .05	1.2	−4.0	−9.8	−10.2	−9.9	−1.6	4.2	6.9	6.1	6.3	6.3	4.5
				P_g	13.0	13.0	12.5	12.0	14.0	14.0	13.5	13.5	15.0	13.0	13.0	13.0
				c	0.2	0.2	−0.7	−1.2	0.8	0.1	−0.9	−0.2	1.2	−0.2	0.0	0.7
				±.64	1.4	−3.8	−10.5	−11.4	−9.1	−1.5	3.3	6.7	7.3	6.1	6.3	5.2

4a. ATLANTIC: Sweden, East

Mem (Sw)	58°29N	16°25E	1887–1924	38	2.9	2.0	−4.7	−9.7	−9.7	−5.3	3.7	9.7	4.8	0.4	−1.1	6.4
Nedre Nyköping (Sw)	58°45N	17°01E	1909–20	12	6.8	−0.7	−9.4	−9.3	−9.6	−2.4	3.5	7.8	7.1	−0.4	−0.8	7.6
Landsort (Sw)	58°45N	17°52E	1887–1946	60	2.3	−0.3	−9.6	−12.0	−12.5	−3.6	5.5	9.2	7.2	4.6	2.0	6.6
N. Södertälje (Sw)	59°12N	17°38E	1869–1946	78	3.3	−1.2	−8.6	−12.3	−12.3	−2.7	5.7	8.8	7.0	4.3	2.5	5.6
Stockholm (Sw)	59°19N	18°05E	1889–1946	58	3.3	0.6	−8.9	−10.5	−12.2	−3.7	5.2	9.0	6.8	4.1	1.9	5.0
Grönskär (Sw)	59°17N	19°02E	1922–30	9	4.0	−9.1	−20.0	−17.8	−13.6	1.8	7.2	10.9	8.3	10.2	12.7	5.1
Björn (Sw)	60°38N	17°58E	1892–1946	55	4.4	0.3	−9.8	−11.5	−13.7	−5.1	4.2	8.3	7.2	4.6	3.5	7.1
Nedre Gävle (Sw)	60°41N	17°10E	1896–1946	51	5.7	−1.1	−9.3	−11.6	−12.3	−5.8	4.8	8.4	6.1	4.0	2.7	8.2
Draghällan (Sw)	62°20N	17°28E	1898–1946	49	6.3	0.4	−10.1	−12.1	−13.4	−5.6	4.2	8.0	9.7	3.3	3.0	6.4
Ratan (Sw)	64°00N	20°55E	1892–1946	55	6.9	1.8	−9.4	−12.0	−14.6	−6.2	2.2	6.4	6.8	4.3	5.4	8.0
				k = .05	4.4	−0.2	−9.4	−11.7	−12.5	−4.2	4.6	8.6	7.1	3.9	2.9	6.6
				P_g	14.0	13.5	13.0	12.5	14.0	14.0	12.5	12.5	15.5	14.0	14.0	13.5
				c	0.8	0.3	0.4	−1.1	0.4	−0.3	−2.3	−1.6	1.3	0.4	0.6	0.8
				±.57	5.2	0.1	−9.0	−12.8	−12.1	−4.5	2.3	7.0	8.4	4.3	3.5	7.4

4b. ATLANTIC: Gulf of Bothnia, North

Station	Latitude	Longitude	Years	Total Years	J	F	M	A	M	J	J	A	S	O	N	D
Furuögrund (Sw)	64°55N	21°14E	1916–46	31	8.8	−2.0	−12.3	−11.6	−10.5	−5.2	0.9	4.4	5.6	5.8	8.7	7.2
Kemi (Fi)	65°44N	24°33E	1920–44(3)	25	9.3	−3.0	−11.7	−16.6	−16.5	−5.4	2.7	6.4	6.0	7.6	11.7	9.8
Toppila (Fi)	65°02N	25°26E	1889–1944(6)	56	9.5	2.8	−8.4	−12.8	−14.9	−6.8	1.4	4.6	6.1	4.0	6.0	8.9
Hornankallio (Fi)	64°42N	24°30E	1922–44(1)	23	8.8	−1.9	−14.4	−15.5	−18.2	−4.9	2.9	5.8	6.5	9.4	11.3	9.9
				k = .09	9.1	−0.7	−11.4	−13.9	−14.8	−5.7	1.9	5.2	6.0	6.4	9.1	8.9
				P_g	8.0	9.5	11.0	11.0	14.0	12.5	11.0	11.0	11.0	11.0	9.5	11.0
				c	−2.4	−0.9	0.2	0.2	3.2	1.0	−1.0	−0.3	−0.4	0.2	−1.1	1.1
				±.86	6.7	−1.6	−11.2	−13.7	−11.6	−4.7	0.9	4.9	5.6	6.6	8.0	10.0

4c. ATLANTIC: Gulf of Bothnia, East

Station	Latitude	Longitude	Years	Total Years	J	F	M	A	M	J	J	A	S	O	N	D
Ykspihlaja (Fi)	63°50N	23°02E	1889–1924	36	6.4	3.2	−7.8	−14.0	−13.3	−5.8	3.1	7.4	8.4	2.2	2.7	7.5
Leppäluoto (Fi)	63°42N	22°42E	1914–44(2)	31	7.0	−1.9	−12.8	−13.8	−16.5	−3.5	2.9	5.9	7.4	7.9	6.8	10.2
Vaasa (Fi)	63°07N	21°36E	1883–1921(2)	39	6.7	3.9	−8.1	−14.5	−14.9	−7.8	2.0	6.6	7.4	3.6	3.3	11.4
Vaskiluoto (Fi)	63°06N	21°34E	1922–44	23	6.3	−3.8	−13.1	−14.2	−15.8	−2.8	4.6	7.3	6.8	8.9	8.7	7.1
Rönnskär (Fi)	63°04N	20°48E	1867–1910, 1920–36	61	7.8	1.1	−9.6	−16.2	−15.1	−6.1	3.3	7.1	6.1	6.8	6.5	7.8
Kaskinen (Fi)	62°23N	21°13E	1926–44(3)	19	3.9	0.1	−11.2	−10.7	−15.9	−4.7	4.7	6.5	4.9	8.8	7.9	6.1
Sälgrund (Fi)	62°20N	21°12E	1919–28(1)	10	12.3	−1.5	−12.1	−17.6	−13.0	−0.2	4.4	9.5	9.6	3.7	2.9	2.1
Reposaari (Fi)	61°37N	21°27E	1889–1926	38	7.1	3.0	−7.3	−12.9	−14.2	−6.4	2.1	7.7	7.9	2.0	2.7	7.9
Mäntyluoto (Fi)	61°36N	21°29E	1910–44(2)	35	4.7	−2.2	−10.0	−11.9	−14.3	−3.0	3.7	6.5	6.7	6.0	6.2	7.2
Säppi (Fi)	61°29N	21°20E	1919–36(2)	18	8.7	−4.6	−15.3	−15.9	−16.2	−2.8	5.3	10.4	6.5	10.7	8.4	4.9
Rauma (Fi)	61°08N	21°29E	1933–44	12	−0.3	0.5	−8.0	−8.3	−14.1	−4.9	5.1	7.2	5.7	6.8	4.8	5.5
				k = .06	6.5	0.1	−10.3	−13.8	−14.9	−4.8	3.5	7.3	7.0	5.9	5.5	7.5
				P_g	12.5	12.5	12.5	12.5	14.0	14.0	11.0	11.0	14.0	12.5	12.5	12.5
				c	0.4	0.4	0.0	0.0	1.5	0.8	−2.7	−2.0	0.9	0.0	0.2	0.9
				±.61	6.9	0.5	−10.3	−13.8	−13.4	−4.0	0.8	5.3	7.9	5.9	5.7	8.4

4d. ATLANTIC: Gulf of Bothnia, Southeast

Lyökki (Fi)	60°51N	21°11E	1858–1936(1)	79	5.9	0.6	−11.5	−14.5	−13.8	−4.9	4.5	8.5	7.6	5.7	5.5	5.8
Lypyrtti (Fi)	60°36N	21°14E	1858–1936(1)	79	5.3	−2.2	−10.2	−14.4	−13.7	−3.4	4.6	8.5	7.2	5.4	5.7	7.0
Ruissalo (Fi)	60°25N	22°06E	1922–44(1)	23	7.4	−11.6	−23.4	−23.7	−24.4	−0.4	10.9	14.4	12.0	16.1	13.4	9.1
Heligman (Fi)	60°12N	19°18E	1920–36(1)	17	7.3	−3.8	−14.0	−14.8	−16.0	−2.9	5.2	9.6	6.0	10.3	9.0	4.2
Strömma (Fi)	60°11N	22°53E	1899–1936(1)	38	7.3	0.0	−11.4	−13.4	−14.1	−5.5	3.5	9.3	7.1	5.7	5.3	6.6
Lemström (Fi)	60°06N	20°01E	1889–1936	48	5.0	1.9	−9.8	−13.0	−14.5	−6.0	4.0	9.2	7.8	4.9	3.8	6.4
Lohm (Fi)	60°06N	21°40E	1920–27(1)	8	11.0	−6.7	−12.5	−14.2	−13.2	1.7	3.9	9.1	10.1	6.0	5.5	−1.2
Degerby (Fi)	60°02N	20°23E	1924–44	21	3.0	−2.4	−10.3	−18.7	−13.9	−2.5	6.9	8.3	7.6	9.8	6.9	4.9
Kobbaklintar (Fi)	60°02N	19°53E	1921–24, 1926–36	15	4.3	−6.2	−15.0	−15.0	−15.2	−2.6	7.2	10.6	5.2	11.7	10.3	4.8
Jungfrusund (Fi)	59°57N	22°22E	1858–1934	77	4.8	−0.3	−10.9	−13.9	−12.6	−3.8	5.5	8.9	7.7	4.5	5.0	5.2
Hanko (Fi)	59°49N	22°58E	1897–1903, 1921–39, 1942–44(1)	29	4.3	0.7	−10.5	−11.6	−13.7	−4.3	4.4	6.3	5.7	7.7	7.2	4.0
Utö (Fi)	59°47N	21°22E	1866–1936(2)	71	4.1	0.2	−10.5	−13.8	−13.9	−4.2	4.8	8.7	7.5	5.1	5.2	6.9
				k = .05	5.5	−1.7	−12.0	−14.8	−14.7	−3.7	5.3	9.1	7.6	7.1	6.4	5.7
				P_g	12.5	12.5	12.5	12.0	14.0	13.0	11.0	11.0	14.0	12.5	12.5	12.5
				c	0.5	0.5	0.1	−0.4	1.6	−0.1	−2.6	−1.9	1.0	0.1	0.3	1.0
				±.71	6.0	−1.2	−11.9	−15.2	−13.1	−3.8	2.7	7.2	8.6	7.2	6.7	6.7

4e. ATLANTIC: Gulf of Finland

Russarö (Fi)	59°46N	22°57E	1866–1924, 1926–36(3)	70	4.4	−0.2	−9.6	−14.1	−12.7	−4.1	4.6	8.4	7.1	4.9	5.0	6.6
Tvärminne (Fi)	59°51N	23°15E	1921–36	16	5.0	−5.4	−14.2	−13.0	−15.8	−3.3	5.9	9.8	6.5	12.0	8.1	3.9
Skuru (Fi)	60°06N	23°33E	1900–36	37	3.4	−6.7	−11.0	−11.2	−11.2	−2.9	5.6	10.7	7.2	5.2	4.9	6.2
Helsinki (Fi)	60°09N	24°58E	1857–62(1), 1879–1944	72	4.1	−1.3	−10.1	−13.7	−13.1	−4.4	5.4	9.1	7.7	5.4	4.4	6.9
Söderskär (Fi)	60°07N	25°25E	1866–1936	71	3.5	−0.9	−11.4	−14.9	−13.0	−3.1	5.5	9.1	8.4	5.3	5.4	6.1
Kotka (Fi)	60°27N	26°57E	1908–12, 1914–27	19	7.3	−1.3	−16.1	−14.0	−12.0	−2.1	1.6	8.6	12.0	5.2	5.8	4.6
Hamina (Fi)	60°34N	27°11E	1928–44(1)	17	0.7	−4.7	−10.3	−11.0	−15.9	−2.4	6.7	8.1	6.7	9.3	6.6	5.8
Viipuri (Fi)	60°42N	28°44E	1889–1939(1), 1943–44(2)	53	3.3	−0.6	−13.3	−15.9	−15.9	−4.5	5.1	9.7	10.3	7.1	8.4	6.0
Koivisto (Fi)	60°21N	28°37E	1922–39(4)	18	3.5	−8.6	−16.5	−17.6	−15.0	−2.2	4.3	7.9	6.5	13.5	9.1	15.1
Suursaari (Fi)	60°05N	26°59E	1920–36(2)	17	3.4	−7.1	−13.4	−15.3	−13.6	1.7	9.1	11.5	8.2	10.6	4.8	0.5
Tallinn (Es)	59°27N	24°48E	1928–38	11	1.8	−1.6	−10.0	−11.9	−17.1	−4.2	8.1	8.8	5.1	12.3	8.7	0.2
				k = .05	3.7	−2.9	−12.0	−14.0	−13.8	−3.1	5.5	9.2	7.9	7.4	6.2	5.9
				P_g	13.5	13.0	13.0	12.5	15.0	12.5	10.5	11.0	13.5	13.5	13.0	13.0
				c	1.2	0.7	0.3	−0.2	2.3	−0.9	−3.4	−2.2	0.2	0.8	0.5	1.2
				±.62	4.9	−2.2	−11.7	−14.2	−11.5	−4.0	2.1	7.0	8.1	8.2	6.7	7.1

4f. ATLANTIC: Baltic Sea, Northeast

Station	Latitude	Longitude	Years	Total Years	J	F	M	A	M	J	J	A	S	O	N	D
Vilsandi (Es)	58°23N	21°49E	1928–38(1)	11	1.6	−3.9	−12.4	−11.1	−15.1	−2.6	1.0	10.0	6.0	14.0	11.1	1.6
Kolkasrags (La)	57°48N	22°38E	1884–93, 1901–13, 1925–36(1)	35	2.7	−1.2	−13.5	−15.1	−14.1	−3.2	6.1	11.2	7.7	7.4	4.7	7.1
Mērsrags (La)	57°20N	23°07E	1929–36	8	−2.0	−6.5	−13.7	−11.4	−14.0	−3.0	10.0	13.7	5.6	14.9	6.1	0.8
Daugavgrīva (La)	57°03N	24°02E	1872–1917, 1922–38(2)	63	−0.8	−3.3	−9.4	−8.2	−8.8	−0.9	7.4	10.5	8.1	2.8	1.3	1.7
Dzirnupe (La)	57°01N	24°07E	1931–36	6	−5.7	0.5	−12.6	−2.2	−9.4	−5.2	7.6	11.2	5.6	13.3	−2.6	−0.6
Andrejosta (La)	56°58N	24°06E	1930–36	7	−3.5	−3.7	−9.9	3.0	−5.6	−8.6	4.3	10.2	0.1	10.8	5.3	−2.4
Ainaži (La)	57°53N	24°20E	1930–36	7	2.8	−1.1	−14.4	−14.4	−17.3	−6.9	7.7	13.4	3.9	16.5	7.9	2.0
Salacgrīva (La)	57°45N	24°22E	1929–36	8	−3.9	−7.1	−4.2	−6.2	−16.2	−5.4	8.0	11.3	3.5	15.5	5.8	−0.8
				k = .09	−0.5	−3.2	−11.1	−9.1	−12.2	−3.8	6.6	11.3	5.8	10.0	4.6	1.9
				P_g	14.0	14.0	14.0	12.5	14.0	14.0	11.0	11.0	14.0	14.0	14.0	14.0
				c	1.1	1.1	0.7	−0.8	0.7	0.0	−3.5	−2.8	0.1	0.7	0.9	1.6
				±1.16	0.6	−2.1	−10.4	−9.9	−11.5	−3.8	3.1	8.5	5.9	10.7	5.5	3.5

4g. ATLANTIC: Baltic Sea, Southeast

Station	Latitude	Longitude	Years	Total Years	J	F	M	A	M	J	J	A	S	O	N	D
Ventspils (La)	57°24N	21°33E	1873–1913, 1920–36(3)	58	2.8	−2.3	−9.2	−13.1	−12.9	−3.8	5.5	10.4	7.5	5.4	5.1	4.8
Pāvilosta (La)	56°54N	21°11E	1930–36	7	1.8	1.9	−13.1	−11.9	−16.6	−8.4	6.0	11.7	3.2	14.7	8.8	1.7
Liepāja (La)	56°32N	20°59E	1865–93, 1896–1913, 1921–38	65	0.9	−3.4	−10.3	−13.4	−11.1	−2.8	6.4	8.7	8.6	5.6	5.5	5.0
Pape (La)	56°09N	21°02E	1930–36	7	1.2	1.8	−12.5	−12.3	−17.3	−9.3	6.1	12.0	3.2	16.3	9.0	1.7
Klaipeda (Li)	55°42N	21°08E	1937–38	2	−6.5	−4.5	6.5	13.0	−10.5	−2.5	9.5	−2.5	4.5	1.5	7.0	−15.5
Memel (Ge)	55°43N	21°07E	1898–1919	22	6.1	3.9	−19.0	−4.1	−12.0	−6.7	3.5	10.4	8.6	−1.0	1.3	9.5
Pillau (Ge)	54°38N	19°54E	1898–1943(1)	46	−0.5	−2.2	−10.1	−8.2	−10.8	−3.9	7.8	11.8	9.1	3.7	0.6	2.7
Hel (Po)	54°36N	18°48E	1931–38	8	−4.8	2.0	−6.9	−5.8	−11.0	−4.3	8.5	11.1	6.2	9.8	1.5	−6.5
Gdynia (Po)	54°32N	18°33E	1931–38	8	−3.2	2.5	−8.3	−17.5	−10.6	−3.6	8.4	10.2	7.7	11.0	3.8	−0.6
				k = .08	0.8	−0.5	−10.7	−10.2	−12.3	−4.7	6.4	10.2	7.3	6.5	4.1	2.9
				P_g	15.5	15.5	15.5	12.5	14.0	13.5	12.5	12.5	15.0	15.0	15.0	14.0
				c	1.8	1.8	1.4	−1.6	−0.1	−1.3	−2.8	−2.1	0.3	0.9	1.1	0.8
				±1.13	2.6	1.3	−9.3	−11.8	−12.4	−6.0	3.6	8.1	7.6	7.4	5.2	3.7

4h. ATLANTIC: Baltic Sea, Central

Limhamn (Sw)	55°35N	12°56E	1928–36(1)	9	−2.2	−3.4	−12.9	−10.8	−11.0	−3.3	7.8	10.1	6.6	13.0	5.2	1.4
Klagshamn (Sw)	55°31N	12°55E	1929–46(1)	18	−0.9	−3.4	−6.5	−3.7	−6.4	−1.9	6.4	8.2	5.1	5.6	0.9	−3.7
Ystad (Sw)	55°25N	13°49E	1887–1946	60	−0.7	−0.6	−7.0	−7.9	−8.2	−2.9	6.3	7.1	6.0	4.7	0.5	3.1
Kungsholms Fort (Sw)	56°06N	15°35E	1887–1946	60	4.4	−0.3	−8.7	−7.7	−10.7	−3.3	4.8	7.8	6.3	4.1	0.4	3.4
Ölands n. udde (Sw)	57°22N	17°06E	1923–46	24	0.2	−2.8	−11.4	−9.8	−11.8	−1.6	6.7	9.0	7.4	8.5	4.4	1.7
Stolpmünde (Ge)	54°35N	16°51E	1911–43	33	0.1	−3.4	−9.6	−8.1	−10.2	−0.7	6.9	9.9	9.0	6.3	−3.0	3.3
Swinemünde (Ge)	53°56N	14°17E	1811–1943(3)	133	−0.3	−2.8	−5.1	−5.7	−6.4	−0.6	7.1	7.9	5.6	0.3	−0.5	0.1
Arkona (Ge)	54°41N	13°26E	1882–1935(6)	54	−1.5	−0.6	−7.0	−8.3	−8.1	−2.3	4.6	7.7	6.5	4.5	1.2	3.4
				k = .05	0.1	−1.9	−7.8	−7.5	−8.7	−1.9	6.2	8.2	6.5	4.7	0.6	1.8
				P_g	15.5	14.5	13.5	12.5	14.0	14.0	13.0	13.0	15.5	14.0	14.0	13.5
				c	1.9	1.0	−0.4	−1.5	0.0	0.3	−2.2	−1.4	0.9	0.0	0.2	0.5
				±.65	2.0	−0.9	−8.2	−9.0	−8.7	−1.6	4.0	6.8	7.4	4.7	0.8	2.3

4i. ATLANTIC: Baltic Sea, West

Warnemünde (Ge)	54°11N	12°05E	1882–1943(3)	62	−3.3	−3.3	−5.3	−5.3	−4.5	1.2	6.3	8.6	6.3	3.0	−1.8	−1.9
Wismar (Ge)	53°54N	11°28E	1882–1943(4)	62	−4.7	−2.6	−6.8	−4.2	−3.1	2.0	6.9	7.9	6.4	2.2	−2.9	−1.3
Travemünde (Ge)	53°58N	10°53E	1855–1943(2)	89	−2.8	−2.0	−3.3	−2.6	−2.1	0.3	3.2	3.9	3.7	4.5	−1.8	−1.0
Marienleuchte (Ge)	54°30N	11°15E	1882–1943(4)	62	−3.3	−1.8	−5.5	−5.1	−4.4	0.3	5.3	7.0	5.7	3.3	−1.8	−0.1
Gedser (De)	54°34N	11°58E	1898–1946	49	−2.5	−2.6	−6.3	−5.2	−4.3	−0.8	5.7	7.9	6.4	3.7	−2.2	0.2
København (De)	55°41N	12°36E	1889–1946(1)	58	−0.8	−3.0	−8.4	−8.0	−8.2	−1.7	5.9	8.1	7.2	5.1	2.2	1.7
Hornbaek (De)	56°06N	12°28E	1898–1946(1)	49	−1.4	−4.9	−10.6	−9.4	−8.7	0.9	7.2	9.2	7.5	6.4	3.6	−0.2
Korsor (De)	55°20N	11°08E	1897–1946	50	−1.3	−2.7	−6.8	−6.3	−5.9	−1.6	4.3	6.3	5.7	4.8	1.7	1.9
Slipshavn (De)	55°17N	10°50E	1896–1946(1)	51	4.8	−2.7	−6.8	−6.6	−6.9	−4.4	3.7	5.5	5.1	4.5	2.8	1.1
Fredericia (De)	55°34N	9°46E	1889–1946(3)	58	−0.2	−2.3	−5.7	−5.8	−6.0	−2.4	2.2	4.1	4.6	5.5	3.8	2.6
Aarhus (De)	56°09N	10°13E	1888–1946(1)	59	5.2	−3.8	−7.0	−7.9	−8.4	−2.8	2.1	4.2	4.1	6.0	4.6	3.3
				k = .04	−0.9	−2.9	−6.5	−6.0	−5.6	−0.8	4.8	6.5	5.7	4.4	0.7	0.5
				P_g	15.5	14.0	12.5	12.5	14.0	14.0	14.0	13.5	15.5	14.0	13.5	13.5
				c	2.1	0.6	−1.3	−1.3	0.2	−0.5	−1.0	−0.8	1.1	0.2	−0.1	0.6
				±.57	1.2	−2.3	−7.8	−7.3	−5.4	−1.3	3.8	5.7	6.8	4.6	0.6	1.1

4. ATLANTIC: Baltic Sea Summary

k = .02	3.0	−1.7	−9.9	−11.1	−11.7	−3.3	5.0	8.3	6.8	5.9	4.0	4.4
c	0.8	0.6	0.2	−0.8	1.1	−0.1	−2.3	−1.7	0.6	0.4	0.2	0.9
±.24	3.8	−1.1	−9.7	−11.9	−10.6	−3.4	2.7	6.6	7.4	6.3	4.2	5.3

5. ATLANTIC: North Sea, West

Station	Latitude	Longitude	Years	Total Years	J	F	M	A	M	J	J	A	S	O	N	D
Aberdeen (Sc)	57°09N	2°05W	1862–1913	52	6.1	0.0	−6.1	−9.2	−9.2	−6.1	−3.1	0.0	0.0	6.1	9.2	12.2
Dundee (Sc)	56°27N	2°58W	1897–1912	16	6.7	1.1	−5.3	−8.8	−10.7	−8.3	−6.4	−0.7	−0.3	8.0	10.9	13.8
Dunbar (Sc)	56°00N	2°31W	1913–46(1)	34	3.1	−2.1	−5.5	−7.0	−7.9	−4.3	−0.9	1.2	2.4	6.4	7.6	6.1
Felixstowe (En)	51°56N	1°19E	1918–46(6)	29	−2.4	−4.6	−4.9	−3.4	−5.2	−1.8	0.6	2.7	4.3	6.4	5.2	2.4
				k = .09	3.5	−1.4	−5.5	−7.2	−8.2	−5.0	−2.3	0.8	1.6	6.7	8.2	8.6
				P_g	14.0	13.0	12.5	12.5	14.0	15.5	15.5	14.0	15.5	12 5	12.5	11.5
				c	0.9	−0.1	−1.0	−1.0	0.5	1.3	0.8	0.0	1.4	−1.0	−0.8	−0.9
				±1.15	4.4	−1.5	−6.5	−8.2	−7.7	−3.2	−1.5	0.8	3.0	5.7	7.4	7.7
6. ATLANTIC: Irish Sea																
Dublin (Ei)	53°21N	6°13W	1938–46	9	3.4	−5.5	−5.2	−5.2	−2.7	−3.1	0.0	−0.9	0.3	7.9	9.4	3.1
Douglas (En)	54°09N	4°28W	1938–46	9	3.7	−4.0	−6.1	−8.5	−6.4	−2.7	−1.2	−0.9	0.3	5.5	12.8	8.8
Liverpool (En)	53°25N	3°00W	1918, 1920, 1924, 1930, 1934–46	17	8.1	−4.7	−8.1	−7.9	−8.0	−3.9	−2.8	−0.6	4.9	8.3	7.8	6.6
Holyhead (En)	53°19N	4°37W	1838–39(2), 1846–47(2), 1938–46(2)	13	8.2	−1.6	−7.4	−8.6	−7.4	−4.3	−4.3	0.5	2.4	8.2	10.0	3.9
Milford Haven (En)	51°42N	4°57W	1886–92	7	−0.2	−11.1	−4.4	−5.9	−1.4	−3.2	0.8	4.4	−1.7	6.0	9.3	7.8
Avonmouth (En)	51°30N	2°43W	1925–46	22	5.4	0.5	−6.3	−6.6	−6.3	−4.5	−0.5	−1.7	3.7	6.8	8.7	1.0
Newlyn (En)	50°06N	5°33W	1916–46	31	1.8	−6.4	−1.1	−3.5	−2.6	−3.7	−2.8	−0.5	0.2	6.2	8.7	3.5
				k = .10	4.4	−4.4	−5.3	−6.4	−5.1	−3.7	−1.7	−0.1	1.6	7.0	9.3	4.5
				P_g	14.0	14.0	13.0	14.5	15.0	17.0	15.5	15.0	16.0	13.5	13.0	12.0
				c	0.1	0.1	−1.3	0.2	0.7	2.0	0.0	0.2	1.1	−0.8	−1.1	−1.4
				±.81	4.5	−4.3	−6.6	−6.2	−4.4	−1.7	−1.7	0.1	2.7	6.2	8.2	3.1
7. ATLANTIC: North Sea, South																
Delfzijl (Ne)	53°20N	6°56E	1865–1946	82	0.3	−3.7	−6.8	−8.0	−8.2	−1.8	2.1	4.5	4.6	6.3	6.6	4.7
Terschelling (Ne)	53°22N	5°13E	1921–46	26	1.2	−4.8	−9.6	−8.4	−9.2	−3.5	1.1	3.3	5.2	10.3	9.4	4.5
Harlingen (Ne)	53°10N	5°25E	1865–1946	82	0.9	−3.6	−7.6	−9.0	−9.9	−3.8	1.6	4.9	5.5	7.6	7.3	6.1
Den Helder (Ne)	52°58N	4°45E	1865–1946	82	1.7	−2.8	−7.1	−8.6	−9.0	−4.2	0.3	1.0	4.6	8.0	8.9	7.3
Ijmuiden (Ne)	52°28N	4°35E	1871–1946	76	0.4	−5.2	−7.3	−7.6	−7.8	−2.7	1.8	4.3	4.6	7.3	7.1	5.1

Hoek van Holland (Ne)	51°59N	4°07E	1864–1946	83	−1.3	−4.1	−5.7	−6.0	−6.4	−1.8	1.6	3.7	3.9	6.3	5.9	3.7
Maassluis (Ne)	51°55N	4°15E	1848–1936	89	0.4	−1.5	−3.7	−5.3	−6.5	−1.9	1.2	2.4	1.8	4.6	4.3	4.4
Hellevoetsluis (Ne)	51°49N	4°08E	1861–1946	86	−2.2	−4.5	−5.6	−5.6	−6.0	−1.7	1.8	3.4	3.1	4.8	5.1	7.2
Brouwershaven (Ne)	51°44N	3°54E	1872–1946	75	−2.1	−5.4	−6.0	−5.5	−5.2	−1.2	2.2	4.1	4.3	6.3	5.5	2.8
Zierikzee (Ne)	51°38N	3°55E	1872–1946	75	−2.7	−5.2	−5.7	−5.2	−4.8	−0.9	2.4	4.2	3.9	5.7	5.4	2.5
Vlissingen (Ne)	51°27N	3°36E	1862–1946	85	−2.4	−4.7	−5.3	−4.6	−4.5	−1.2	2.0	3.8	3.9	6.0	4.7	2.2
				k = .04	−0.6	−4.1	−6.3	−6.6	−7.0	−2.2	1.7	3.6	4.1	6.5	6.2	4.6
				P_g	14.0	14.0	13.0	13.0	14.0	15.0	15.0	14.5	17.0	14.0	14.0	14.0
				c	0.2	0.2	−1.2	−1.2	−0.2	0.1	−0.4	−0.2	2.2	−0.2	0.0	0.7
				±.40	−0.4	−3.8	−7.5	−7.8	−7.2	−2.1	1.3	3.4	6.3	6.3	6.2	5.3
				8.	ATLANTIC: English Channel											
Zeebrugge (Be)	51°21N	3°12E	Aug. 1942–July 1943(2)	1	1.6	3.2	−11.4	−3.0	−12.4	−6.6	0.8	−5.3	5.9	14.1	3.4	9.3
Antwerpen (Be)	51°14N	4°25E	1937–38, 1943–44(2)	4	8.2	7.5	−2.7	−1.4	−4.2	−7.4	−1.9	1.3	−0.6	2.3	6.3	−7.8
Ostende (Be)	51°14N	2°55E	1937–38, 1943–Jan. 1944(1)	3	6.4	−0.1	−4.6	−3.0	−5.8	−2.1	−1.0	0.8	−0.1	2.8	9.9	−0.5
Nieuport (Be)	51°09N	2°43E	1943	1	6.5	4.0	−5.2	1.4	−8.9	−8.9	−3.9	4.4	−0.8	2.7	13.5	−6.6
Dunkerque (Fr)	51°03N	2°22E	1942	1	−12.9	−14.8	−10.6	−8.3	0.9	−4.4	4.1	2.5	7.6	15.5	8.5	11.6
Calais (Fr)	50°58N	1°51E	June 1941–May 1942(2)	1	−10.2	−9.2	2.5	−23.8	−12.3	3.6	7.6	12.4	0.9	15.6	5.8	7.4
Boulogne (Fr)	50°44N	1°35E	1942	1	−12.5	−22.9	−8.9	−0.9	2.2	−5.2	41.0	15.1	−1.7	5.5	−13.2	1.2
Dieppe (Fr)	49°56N	0°21E	1942	1	−7.7	−18.0	−7.3	−7.8	0.2	−6.1	0.6	2.9	16.6	18.8	−0.4	8.6
Fecamp (Fr)	49°46N	0°21E	1942	1	−7.8	−15.9	−5.1	−6.5	2.1	−2.4	2.4	2.2	9.8	11.6	−1.2	10.9
Le Havre (Fr)	49°29N	0°06E	Dec. 1941–Nov. 1942(2)	1	−25.4	−4.4	15.9	2.7	0.6	5.5	10.1	−5.3	9.3	13.0	0.1	−22.3
Cherbourg (Fr)	49°39N	1°37W	1943	1	−31.9	−40.1	−21.8	−18.8	17.3	10.0	12.1	12.0	19.2	19.7	2.9	19.9
Guernsey (Fr)	49°27N	2°31W	1943	1	−11.7	−40.8	−35.8	−33.9	−8.6	10.7	15.9	21.3	22.0	31.6	21.8	8.0
Jersey (Fr)	49°14N	2°12W	Sept. 1943–Apr. 1944(2)	1	−7.1	−8.1		1.0					4.5	14.3	5.1	−9.6
St. Malo (Fr)	48°38N	2°02W	June 1942–May 1943(2)	1	14.7	−13.7	−9.9	−13.1	−9.8	13.9	3.2	0.4	1.5	5.2	−3.5	11.3
Lizardrieux (Fr)	48°47N	3°06W	1942	1	0.3	−10.1	−1.0	−6.8	−1.9	−7.9	−2.9	4.2	10.9	12.5	−3.5	6.6
Brest (Fr)	48°23N	4°29E	1807–35, 1846–56, 1861–1943	123	0.8	−2.0	−3.1	−3.1	−2.6	−3.7	−3.1	−1.7	0.6	6.4	6.8	4.5
				k = .14	−2.4	−7.1	−5.3	−5.7	−2.9	−2.1	1.9	1.9	4.0	9.3	5.2	3.2
				P_g	17.0	18.5	14.0	14.0	14.0	17.0	17.0	16.0	18.0	15.0	15.0	14.0
				c	1.7	3.2	−1.7	−1.7	−1.7	0.6	0.1	−0.2	1.7	−0.7	−0.5	−0.8
				±1.93	−0.7	−3.8	−7.0	−7.4	−4.6	−1.5	2.0	1.7	5.7	8.6	4.7	2.4

9. ATLANTIC: Bay of Biscay

Station	Latitude	Longitude	Years	Total Years	J	F	M	A	M	J	J	A	S	O	N	D
Lorient (Fr)	47°45N	3°21W	1942	1	−12.1	−8.5	2.3	3.0	3.4	−1.2	7.2	−3.2	−1.8	3.5	−2.7	9.9
St. Nazaire (Fr)	47°16N	2°12W	Apr. 1941–Mar. 1942(2)	1	−3.1	−8.8	6.9	2.2	−2.2	5.2	3.8	3.1	−8.1	−4.9	11.6	−5.9
La Pallice (Fr)	46°10N	1°13W	1942	1	−11.1	−15.3	−0.8	−1.5	4.8	1.4	−3.7	0.7	7.6	12.2	−0.2	6.1
Le Verdon (Fr)	45°33N	1°04W	1941–42(1)	2	−7.9	−11.9	4.5	5.5	2.9	1.0	−6.3	2.5	5.6	6.3	2.5	−4.3
St. Jean-de-Luz (Fr)	43°24N	1°41W	1942–44(3)	3	−5.6	−5.2	−4.2	−2.3	−5.4	15.9		−1.5	−0.2	9.7	−0.9	−0.2
				k = .36	−7.6	−9.2	0.8	0.8	−0.3	6.4	0.2	0.0	0.5	6.1	1.6	0.9
				P_g	18.5	18.5	15.5	15.5	15.5	18.5	17.5	17.0	18.0	15.5	15.5	17.0
				c	2.1	2.1	−1.3	−1.3	−1.3	1.0	−0.5	−0.3	0.6	−1.3	−1.1	1.1
				±2.11	−5.5	−7.1	−0.5	−0.5	−1.6	7.4	−0.3	−0.3	1.1	4.8	0.5	2.0

10. ATLANTIC: Iberian Peninsula

Station	Latitude	Longitude	Years	Total Years	J	F	M	A	M	J	J	A	S	O	N	D
Cascais (Po)[1]	38°41N	9°25W	1917–46(2)	30	−3.6	−5.2	−0.9	−0.5	−0.6	−1.9	−1.2	0.9	2.7	6.5	4.8	−0.5
Lagos (Po)[1]	37°06N	8°40W	1908–46(8)	39	−4.3	−5.3	−3.4	−3.3	−3.1	0.7	0.1	1.9	4.0	6.5	5.4	0.6
Cadiz (Sp)	36°30N	6°18W	1916–19(4)	4	0.7	0.5	−3.5	2.3	0.8	1.6	−2.5	−7.3	−2.9	−1.0	7.4	3.5
				k = .13	−3.3	−4.4	−2.5	−1.4	−1.5	−0.1	−0.8	0.1	2.4	5.7	5.5	0.7
				P_g	23.0	20.0	18.5	17.0	17.0	18.5	18.5	18.5	18.5	18.0	18.5	21.0
				c	4.6	1.6	−0.3	−1.8	−1.8	−1.0	−1.5	−0.8	−0.9	−0.8	−0.1	3.1
				±1.10	1.3	−2.8	−2.8	−3.2	−3.3	−1.1	−2.3	−0.7	1.5	4.9	5.4	3.8

11a. ATLANTIC: Mediterranean, North

Station	Latitude	Longitude	Years	Total Years	J	F	M	A	M	J	J	A	S	O	N	D
Alicante (Sp)	38°20N	0°29W	1916–20	5	−5.2	−6.0	−3.4	−3.2	−2.0	−4.9	1.6	3.4	3.2	6.4	8.4	1.5
Marseille (Fr)	43°18N	5°21E	1885–1946(1)	62	−1.4	−2.3	−2.5	−1.5	−1.4	−1.8	−2.6	−2.3	−1.1	4.8	7.8	3.9
Porto Maurizio (It)	43°52N	8°01E	1896–1922(4)	27	−3.0	−4.0	−2.9	−1.6	−1.9	−0.2	−0.3	0.3	0.6	4.3	6.1	2.8
Genova (It)	44°25N	8°55E	1883–1910, 1928–45(4)	46	−2.9	−2.0	−0.3	0.8	−3.2	−1.9	1.2	1.2	−2.3	3.4	4.1	2.3
Livorno (It)	43°32N	10°18E	1896–1911	16	−5.7	−4.1	−2.5	−0.9	−0.4	0.8	−1.4	−0.7	0.0	5.0	6.0	4.3
Civitavecchia (It)	42°03N	11°49E	1896–1922(6)	27	−1.3	−1.8	−1.9	−0.5	−2.1	−2.2	−2.6	−1.8	−0.7	3.9	6.5	4.5
Napoli (Arsenale) (It)	40°52N	14°16E	1899–1922(13)	24	−1.5	−1.2	−2.0	−1.2	−2.4	−1.0	−1.8	−0.6	−0.8	3.4	5.9	3.7
Napoli (Mandraccio) (It)	40°52N	14°16E	1896–1922(9)	27	−1.9	−3.1	−2.4	−0.6	−1.5	−1.1	−1.8	−0.5	−1.1	3.8	6.3	4.5
Messina (Si)	38°12N	15°34E	1897–1923(3)	27	−0.1	−0.7	−2.9	−1.4	−3.1	−2.4	−2.7	−0.8	−1.0	3.7	6.5	5.4
				k = .06	−2.2	−2.5	−2.2	−0.9	−2.0	−1.5	−1.3	−0.5	−0.7	4.1	6.3	3.7
				P_g	20.0	17.0	15.5	14.0	15.5	15.5	15.5	15.5	17.0	17.0	15.5	17.0
				c	4.2	1.2	−0.7	−2.2	−0.7	−1.4	−1.9	−1.2	0.2	0.8	−0.5	1.7
				±.39	2.0	−1.3	−2.9	−3.1	−2.7	−2.9	−3.2	−1.7	−0.5	4.9	5.8	5.4

11b. ATLANTIC: Mediterranean, Sardinia

La Maddalena (Sa)	41°14N	9°22E	1896–98, 1900–13(7)	17	−6.7	−7.3	−5.4	−3.3	−1.8	1.3	2.3	4.8	3.8	6.2	4.6	1.7
Cagliari (Sa)	39°12N	9°10E	1896–1934(12)	39	−6.8	−5.7	−5.6	−3.8	−2.6	−0.1	1.7	4.7	4.9	6.6	6.0	1.1
				k = .14	−6.8	−6.3	−5.5	−3.6	−2.3	−0.5	1.9	4.7	4.5	6.4	5.4	1.3
				P_g	18.5	15.5	14.0	13.0	14.0	14.0	15.0	14.0	15.5	15.5	15.5	17.0
				c	3.9	0.9	−1.0	−2.0	−1.0	−1.7	−1.2	−1.5	−0.1	0.5	0.7	2.9
				±.32	−2.9	−5.4	−6.5	−5.6	−3.3	−2.2	0.7	3.2	4.4	6.9	6.1	4.2

11c. ATLANTIC: Mediterranean, Sicily

Mazara del Vallo (Si)	37°40N	12°34E	1909–16(2)	8	2.0	−1.8	−1.2	−5.8	−4.8	−3.8	−4.9	−2.9	−0.7	4.6	11.6	7.5
Palermo (Si)	38°08N	13°20E	1896–1922(11)	27	−0.7	−1.6	−3.1	−1.6	−2.8	−1.9	−2.2	−0.7	0.8	5.2	6.3	2.9
Catania (Si)	37°30N	15°08E	1896–1920(9)	25	−1.5	−1.1	−3.0	−3.2	−4.1	−2.3	−0.7	1.6	1.1	3.6	5.7	4.5
				k = .13	−0.4	−1.4	−2.6	−3.2	−3.8	−2.5	−2.2	−0.3	0.6	4.4	7.3	4.6
				P_g	17.0	15.5	14.0	14.0	14.0	14.0	14.0	14.0	15.5	16.0	15.5	17.0
				c	2.4	0.9	−1.0	−1.0	−1.0	−1.7	−2.2	−1.5	−0.1	1.0	0.7	2.9
				±.77	2.0	−0.5	−3.6	−4.2	−4.8	−4.2	−4.4	−1.8	0.5	5.4	8.0	7.5

11d. ATLANTIC: Mediterranean, Adriatic

Taranto (It)	40°26N	17°16E	1906–11	6	−7.5	−0.5	−3.1	−1.9	1.6	0.9	−0.8	1.3	3.0	0.3	4.0	3.0
Ancona (It)	43°35N	13°29E	1896–1910(7)	15	−2.2	−0.4	−3.6	−1.6	−2.0	−1.5	−3.4	−3.3	−2.9	5.5	7.6	7.3
Porto Corsini (It)	44°30N	12°17E	1896–1922(3), 1937–42	33	−1.7	−2.1	−3.2	−0.1	−2.1	−1.0	−3.4	−3.2	−2.8	4.7	8.7	5.6
Venezia (Diga Sud di Lido) (It)	45°21N	12°23E	1917–34	18	−2.6	−6.1	−5.2	−0.4	−2.3	−0.3	−0.7	−1.1	−0.6	6.5	9.3	4.3
Venezia (Arsenale) (It)	45°24N	12°21E	1889–1913(7)	25	−4.1	−5.8	−2.7	−1.1	−0.4	0.0	−1.3	−1.3	−0.7	6.8	6.7	3.4
Venezia (S. Stefano) (It)	45°25N	12°20E	1896–1920(4)	25	−4.4	−5.3	−3.2	−0.1	−0.8	0.3	−1.3	−2.0	−1.4	5.5	7.1	5.4
Trieste (It)	45°39N	13°46E	1905–14, 1920–22, 1927–36(2)	23	−5.4	−8.0	−4.7	−0.3	−0.2	1.4	−0.4	−0.4	−0.2	5.7	9.5	3.8
Pola (It)	44°52N	13°51E	1897–1910, 1912–13	16	−5.4	−2.0	−3.7	−1.5	−1.3	0.6	−1.6	−1.7	−1.0	5.1	7.2	5.1
Bakar (Yu)	45°18N	14°32E	1930–38(2)	9	−10.1	−8.7	−9.7	−8.5	−9.0	−8.8	9.8	8.4	1.4	9.2	12.0	8.0
Split (Yu)	43°30N	16°27E	1930–38(2)	9	2.4	2.8	0.9	1.6	0.1	−1.7	−2.3	−3.2	−11.8	4.6	9.6	−3.2
				k = .08	−3.9	−3.9	−3.8	−1.1	−1.6	−0.8	−0.9	−1.1	−1.7	5.6	8.2	4.5
				P_g	17.0	15.5	15.5	13.5	14.0	14.0	14.0	14.0	15.5	17.0	17.0	17.0
				c	2.1	0.6	0.2	−1.8	−1.3	−2.0	−2.5	−1.8	−0.4	1.7	2.1	2.6
				±.82	−1.8	−3.3	−3.6	−2.9	−2.9	−2.8	−3.4	−2.9	−2.1	7.3	10.3	7.1

11e. ATLANTIC: Mediterranean, East

Station	Latitude	Longitude	Years	Total Years	J	F	M	A	M	J	J	A	S	O	N	D
Port Said (Su)	31°15N	32°18E	1923–46(1)	24	−2.1	−5.2	−9.4	−10.1	−7.8	−1.6	6.6	10.3	7.3	4.3	5.4	2.3
				k = .20												
				P_g	17.6	16.6	14.5	12.5	13.2	11.8	9.1	9.8	13.5	14.5	16.6	16.9
				c	4.2	3.2	0.7	−1.3	−0.6	−2.7	−5.9	−4.5	−0.9	0.7	3.0	4.0
					2.1	−2.0	−8.7	−11.4	−8.4	−4.3	0.7	5.8	6.4	5.0	8.4	6.3

11. ATLANTIC: Mediterranean Sea Summary

	J	F	M	A	M	J	J	A	S	O	N	D
k = .04	−3.0	−3.3	−3.4	−1.9	−2.4	−1.2	−0.6	−0.1	−0.1	4.9	7.0	3.8
c	3.4	1.4	−0.4	−1.7	−0.9	−1.9	−2.7	−2.1	−0.3	0.9	1.2	2.8
±.36	0.4	−1.9	−3.8	−3.6	−3.3	−3.1	−3.3	−2.2	−0.4	5.8	8.2	6.6

12. ATLANTIC: Azores

Station	Latitude	Longitude	Years	Total Years	J	F	M	A	M	J	J	A	S	O	N	D
Horta (Az)	38°32N	28°38W	1905–38(7), 1945	35	0.0	−1.9	−4.0	−3.6	−2.7	−0.5	1.1	2.7	3.2	3.0	1.6	0.7
Angra do Heroismo (Az)	38°38N	27°12W	1933–37(1)	5	−0.9	−2.9	−3.6	−6.1	−1.5	−2.8	−0.5	0.5	3.2	4.6	5.3	4.2
Ponta Delgada (Az)[2]	37°44N	25°40W	1924, 1930–51(4)	23	0.0	−2.9	−3.8	−3.6	−4.3	−1.6	0.5	2.5	4.1	4.1	2.7	2.4
				k = .07	−0.1	−2.4	−3.9	−4.0	−3.1	−1.3	0.6	2.3	3.5	3.7	2.6	1.9
				P_g	17.0	14.0	15.0	15.5	17.0	17.0	18.5	18.5	18.5	18.5	17.0	17.0
				c	0.5	−2.5	−1.9	−1.4	0.1	−0.6	0.4	1.1	1.0	1.6	0.3	1.0
				±.46	0.4	−4.9	−5.8	−5.4	−3.0	−1.9	1.0	3.4	4.5	5.3	2.9	2.9

13. ATLANTIC: Canary Islands

Station	Latitude	Longitude	Years	Total Years	J	F	M	A	M	J	J	A	S	O	N	D
Santa Cruz de Tenerife (CI) (a)[2,3]	28°29N	16°14W	1927–36(1), 1940–46(1)	17	−7.3	−6.2	−4.4	−1.9	−2.0	0.4	4.5	6.8	6.1	5.8	1.0	−2.9
Santa Cruz de Tenerife (CI) (b)[2,3]	28°29N	16°14W	1926–36(3), 1940–46(1)	18	−7.8	−6.7	−4.7	−1.8	−1.5	0.8	5.1	7.1	6.1	6.1	1.2	−3.8
				k = .17	−7.6	−6.4	−4.6	−1.8	−1.8	0.6	4.8	7.0	6.1	6.0	1.1	−3.4
				P_g	22.5	20.0	18.5	18.5	17.0	17.0	17.0	17.0	17.0	17.0	18.5	21.5
				c	4.4	2.0	0.1	0.1	−1.4	−2.1	−2.6	−1.9	−2.0	−1.4	0.3	4.0
				±.17	−3.1	−4.4	−4.5	−1.7	−3.2	−1.5	2.2	5.1	4.1	4.6	1.4	0.6

				14. ATLANTIC: Cape Verde Islands												
Porto Grande (CVI)[3] (St. Vincent)	16°53N	25°00W	1947–50	4	−3.3	−3.9	−2.1	−0.3	0.3	−0.1	0.2	1.4	1.7	2.0	2.6	1.2
				k = .50												
				P_g	17.0	17.0	16.5	16.0	16.0	16.5	16.5	15.0	15.5	15.5	15.5	16.0
				c	1.4	1.4	0.5	0.0	0.0	−0.2	−0.7	−1.5	−1.1	−0.5	−0.3	0.9
					−1.9	−2.5	−1.6	−0.3	0.3	−0.3	−0.5	−0.1	0.6	1.5	2.3	2.1
				15. ATLANTIC: Sierra Leone												
Freetown (SL)[4]	8°30N	13°14W	Feb. 1926–Jan. 1927(2)	1	−7.7	−3.0	−7.9	−5.3	−0.3	3.9	2.5	3.6	1.9	6.1	7.0	−0.7
				k = 1.00												
				P_g	14.0	11.0	11.0	11.0	11.0	12.5	13.0	12.5	12.5	12.5	11.0	11.0
				c	2.6	−0.4	−0.8	−0.8	−0.8	0.0	0.0	0.2	0.1	0.7	−0.6	0.1
					−5.1	−3.4	−8.7	−6.1	−1.1	3.9	2.5	3.8	2.0	6.8	6.4	−0.6
				16. ATLANTIC: Gulf of Guinea, Africa												
Takoradi (GC)	4°53N	1°45W	1929–46(1)	18	0.4	3.4	4.5	4.3	−0.4	−5.8	−9.8	−10.0	−4.8	5.5	9.8	2.6
Accra (GC)	5°32N	0°12W	Apr. 1922–Apr. 1923, 1938(2)	2	0.6	6.4	6.4	5.1	−1.6	−7.4	−14.7	−11.3	−0.4	6.7	10.3	0.0
Lagos (Ni)	6°24N	3°24E	Apr. 1940–Mar. 1941(2)	1	−0.1	−0.4	−1.6	−0.4	−0.4	−1.0	−8.9	−5.9	2.1	12.4	7.4	−3.4
Forcados (Ni)	5°22N	5°26E	Sept. 1934–Aug. 1935(2)	1	−7.8	1.0	2.3	5.3	−2.0	−2.9	−1.1	−2.0	1.7	5.0	5.6	−5.1
Port Harcourt (Ni)	4°46N	7°00E	Mar. 1935–Feb. 1936(2)	1	−3.8	−9.3	6.6	5.7	−2.6	−4.7	−4.1	−2.0	0.2	11.2	6.0	−3.2
Calabar (Ni)	4°58N	8°19E	1937	1	−5.1	−8.5	−1.4	−3.3	−13.6	−7.2	3.7	5.3	15.0	19.9	3.1	−7.8
				k = .25	−1.6	0.3	3.4	3.3	−2.4	−5.2	−7.1	−6.2	−0.1	8.6	8.0	−1.0
				P_g	12.4	12.4	10.7	12.4	10.4	10.4	14.0	12.4	12.4	10.7	12.4	12.4
				c	1.0	1.0	−1.1	0.6	−1.4	−2.1	1.0	0.1	0.0	−1.1	0.8	1.5
				±1.69	−0.6	1.3	2.3	3.9	−3.8	−7.3	−6.1	−6.1	−0.1	7.5	8.8	0.5
				17. ATLANTIC: Cape of Good Hope												
Capetown (SA)[5]	33°54S	18°25E	1888	1	−2.9	−2.0	3.2	1.3	−0.8	−2.0	−8.1	0.1	−1.4	5.6	6.2	0.4
				k = 1.00												
				P_g	13.9	14.9	15.9	17.6	17.6	19.3	20.0	20.0	18.3	17.6	17.6	15.2
				c	−2.9	−1.9	−1.3	0.4	0.4	1.4	1.6	2.3	0.5	0.4	0.6	−1.1
					−5.8	−3.9	1.9	1.7	−0.4	−0.6	−6.5	2.4	−0.9	6.0	6.8	−0.7

(485)

18. ATLANTIC: Magellan Strait

Station	Latitude	Longitude	Years	Total Years	J	F	M	A	M	J	J	A	S	O	N	D
Punta Arenas (Ch)[5]	53°09S	70°54W	1942–46(4)	5	−2.9	.4.7	3.5	−1.5	6.6	0.7	−0.8	−8.1	−5.2	2.4	−1.1	1.6
				k = .45												
				P_s	99.9	99.0	99.0	1.7	2.0	1.4	1.0	0.7	3.0	99.0	98.3	98.0
				c	0.1	−0.8	−1.2	1.5	1.8	0.5	−0.4	0.0	2.2	−1.2	−1.7	−1.3
					−2.8	3.9	2.3	0.0	8.4	1.2	−1.2	−8.1	−3.0	1.2	−2.8	0.3
				19. ATLANTIC: Argentina, South												
Deseado (Ar)[6]	47°45S	65°55W	1912–37(14)	26	6.2	1.6	−2.2	1.8	2.4	0.2	−0.9	−4.3	−4.8	−10.1	5.5	4.5
Comodoro Rivadavia	45°52S	67°29W	1911–19(3), 1926–41(6)	25	0.6	4.4	5.4	−0.3	−3.6	−1.5	0.1	−3.8	−4.6	−3.3	2.7	3.9
Puerto Madryn (Ar)	42°46S	65°02W	1944–46(1)	3	3.9	10.9	5.4	−4.1	1.9	7.4	−8.6	−5.9	−7.9	−2.3	−3.6	2.7
San Antonio (Ar)	40°48S	64°52W	1910–24(8)	15	7.4	5.7	2.5	−1.1	3.3	6.6	−4.4	−8.1	−7.0	−9.1	3.4	0.8
				k = .13	4.5	4.7	2.3	−0.3	0.7	2.2	−2.4	−5.3	−5.7	−6.8	3.0	3.2
				P_s	7.1	10.1	9.1	8.5	8.1	9.8	10.8	9.8	10.8	9.8	9.8	4.7
				c	−1.4	1.6	0.2	−0.4	−0.8	0.2	0.7	0.4	1.3	0.9	1.1	−3.3
				±1.34	3.1	6.3	2.5	−0.7	−0.1	2.4	−1.7	−4.9	−4.4	−5.9	4.1	−0.1
				20. ATLANTIC: Argentina, Transition												
Belgrano (Ar)	38°53S	62°06W	1914–36(4), 1938	24	7.6	7.5	6.4	2.8	2.4	−1.3	−4.7	−7.7	−9.4	−5.9	−0.5	3.3
Quequén (Ar)	38°35S	58°42W	1910–46(7)	37	5.2	4.8	5.3	1.2	6.0	3.2	−2.1	−7.1	−10.5	−7.6	−1.0	2.1
Mar Del Plata (Ar)	38°03S	57°33W	1910–13(2), 1915–46(2)	36	4.3	4.9	4.5	5.3	4.9	−0.3	−2.8	−6.4	−9.4	−6.0	−0.1	1.5
				k = .10	5.6	5.6	5.3	3.1	4.6	0.6	−3.1	−7.0	−9.8	−6.5	−0.5	2.2
				P_s	9.8	12.8	13.2	14.2	12.8	15.2	15.9	15.9	16.6	13.9	12.8	9.5
				c	−3.3	−0.3	−0.3	0.7	−0.7	1.0	1.2	1.9	2.5	0.4	−0.5	−3.1
				±.66	2.3	5.3	5.0	2.4	3.9	1.6	−1.9	−5.1	−7.3	−5.1	−1.0	−0.9

21. ATLANTIC: North Brazil Current																
La Plata (Ar)	34°55S	57°56W	1916–34	19	6.9	6.9	5.9	4.9	−0.1	−5.1	−7.1	−6.1	−5.1	−4.1	−0.1	2.9
Buenos Aires (Ar)	34°36S	58°22W	1905–43, 1945–46	41	7.5	7.2	7.3	4.8	−2.0	−7.6	−10.1	−4.9	−3.0	−1.9	−0.1	2.5
Puerto de Colonia (Ur)	34°29S	57°51W	1938–46	9	7.8	4.1	7.0	6.4	−1.6	−4.6	−9.2	−3.4	−6.2	0.2	−1.2	0.9
Montevideo (Ur)	34°53S	56°16W	1938–46	9	2.8	2.1	6.2	9.4	2.4	1.9	−6.2	−1.5	−8.0	−5.7	−2.6	−0.7
Puerto de Punta del Este (Ur)	34°58S	54°57W	1938–45	8	0.3	1.4	5.3	10.9	5.2	4.3	−6.0	−1.8	−11.7	−6.5	0.0	−1.6
				k = .11	5.5	4.9	6.5	6.8	0.3	−3.2	−8.1	−3.9	−6.1	−3.4	−0.7	1.2
				P_g	11.8	12.8	14.2	15.6	15.9	17.6	17.6	17.6	16.6	14.9	13.2	11.5
				c	−2.6	−1.6	−0.6	0.8	1.1	2.1	1.6	2.3	1.0	0.1	−1.4	−2.5
				±1.09	2.9	3.3	5.9	7.6	1.4	−1.1	−6.5	−1.6	−5.1	−3.3	−2.1	−1.3
22. ATLANTIC: British Guiana																
Georgetown (Gu)	6°48N	58°10W	May 1927–Apr. 1928(2)	1	4.0	3.4	−2.4	−1.2	−4.3	−3.4	−4.0	−0.3	0.9	0.3	2.1	4.9
				k = 1.00												
				P_g	10.7	12.4	10.7	10.7	10.7	10.7	10.7	10.7	10.7	10.7	8.9	10.7
				c	0.5	2.2	0.1	0.1	0.1	−0.6	−1.1	−0.4	0.0	0.1	−1.5	1.0
					4.5	5.6	−2.3	−1.1	−4.2	−4.0	−5.1	−0.7	0.9	0.4	0.6	5.9
23. ATLANTIC: Venezuela																
Port of Spain (Tr)	10°39N	61°31W	Nov. 1937–Oct. 1938(2)	1	−12.8	−16.3	−9.6	−7.6	−1.7	3.0	5.1	9.0	8.4	11.3	11.1	0.1
Zaparita (Ve)	11°01N	71°39W	1939–46(3)	8	−4.5	−4.1	−5.2	−3.4	−0.4	0.6	0.4	0.3	1.0	5.6	7.7	1.9
Tablazo (Ve)	10°53N	71°37W	1944–46	3	−10.5	−13.5	−13.8	−5.3	4.8	8.1	5.1	1.4	1.4	5.7	11.5	5.4
Zapara Island (Ve)	10°58N	71°34W	1929–36(4), 1938–39, 1941	11	−6.4	−9.3	−9.0	−5.4	0.2	2.1	−0.1	2.1	4.5	7.5	11.1	2.3
				k = .22	−7.4	−9.3	−8.9	−5.0	0.8	3.0	1.8	2.1	3.1	6.9	10.1	2.6
				P_g	13.5	14.0	13.5	13.0	13.0	13.0	13.5	13.0	12.0	11.5	12.5	13.0
				c	1.0	1.5	0.6	0.1	0.1	−0.6	−0.6	−0.4	−1.5	−1.4	−0.2	1.0
				±1.27	−6.4	−7.8	−8.3	−4.9	0.9	2.4	1.2	1.7	1.6	5.5	9.9	3.6
24. ATLANTIC: Panama Canal Zone																
Cristobal (CZ)	9°21N	79°55W	1909–46	38	−0.4	−2.2	−2.7	−2.6	−1.9	−1.7	−0.4	0.5	1.6	3.4	5.1	1.5
				k = .16												
				P_g	11.0	14.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0
				c	0.2	3.2	−0.2	−0.2	−0.2	−0.9	−1.4	−0.7	−0.8	−0.2	0.0	0.7
					−0.2	1.0	−2.9	−2.8	−2.1	−2.6	−1.8	−0.2	0.8	3.2	5.1	2.2

Station	Latitude	Longitude	Years	Total Years	J	F	M	A	M	J	J	A	S	O	N	D
				25. ATLANTIC: Gulf of Mexico, West												
Galveston (US)	29°19N	94°47W	1908–46(1)	39	−11.2	−9.3	−5.7	1.1	5.9	4.1	−4.5	−1.7	13.2	12.9	1.8	−6.1
				k = .16												
				P_g	21.0	18.5	17.0	15.5	15.5	15.5	17.0	15.5	15.5	17.0	20.0	20.0
				c	4.1	1.6	−0.3	−1.8	−1.8	−2.5	−1.5	−2.3	−2.4	−0.3	2.9	3.6
					−7.1	−7.7	−6.0	−0.7	4.1	1.6	−6.0	−4.0	10.8	12.6	4.7	−2.5
				26. ATLANTIC: Gulf of Mexico, East												
Pensacola (US)	30°24N	87°13W	1923–46(1)	24	−10.5	−10.1	−6.7	−2.0	1.2	3.0	2.5	7.0	12.3	9.6	0.6	−6.7
Cedar Keys (US)	29°08N	83°02W	1914–25(1)	12	−9.8	−10.0	−6.6	−3.2	1.8	5.1	8.6	8.5	8.9	4.1	−0.2	−7.1
Key West, C. Wharf (US)	24°34N	81°48W	1913–25	13	−7.0	−6.7	−6.3	−4.5	−1.2	−0.6	−0.9	2.8	9.8	10.7	6.5	−2.1
Key West, Naval Base	24°33N	81°48W	1926–46(2)	21	−6.2	−8.2	−8.0	−4.2	−2.5	−1.8	−1.5	3.6	8.9	13.0	7.6	−0.3
				k = .12	−8.3	−8.7	−7.0	−3.4	−0.3	1.1	1.6	5.3	10.1	9.9	3.9	−3.8
				P_g	21.0	18.5	17.0	15.5	15.5	15.5	17.0	15.5	15.5	17.0	20.0	20.0
				c	4.2	1.7	−0.2	−1.7	−1.7	−2.4	−1.4	−2.2	−2.3	−0.2	3.0	3.7
				±1.18	−4.1	−7.0	−7.2	−5.1	−2.0	−1.3	0.2	3.1	7.8	9.7	6.9	−0.1
				27. ATLANTIC: Cuba and Cat Cay												
Havana (Cu)[2]	23°09N	82°20W	1947–51(1)	5	−8.1	−8.6	−3.8	−2.9	−1.4	1.3	0.5	6.3	9.8	6.9	0.5	−3.2
Pinar del Rio (Cu)[2,7]			1949–51(3)	3	−4.8	−12.2	−8.1	1.3	5.6	3.1	6.2		5.2	1.5	−2.6	0.4
Casilda (Cu)[2]	21°45N	79°59W	1949–51	3	−7.1	−8.5	−6.4	−2.8	2.2	2.4	0.9	5.8	10.5	7.1	−0.3	−3.9
Guantanamo Bay (Cu)[2]	19°54N	75°09W	1937–51(4)	14	−4.8	−5.6	−4.4	−3.5	−0.6	−0.7	0.4	2.9	6.8	7.3	4.0	−1.8
Baracoa (Cu)[2]	20°21N	74°30W	1949–51(3)	3	−11.9	−8.9	−5.4	0.1	9.6	6.3	−5.1	5.7	4.3	6.0	5.7	−6.4
Gibara (Cu)[2]	21°07N	76°08W	1949–51	3	−8.0	−9.0	−5.5	−2.0	3.0	0.8	0.4	6.0	7.3	7.0	2.7	−2.7
Cat Cay (Ba)[5]	24°19N	75°26W	1938–41(3), 1950–51(2)	5	−6.2	−6.5	−5.2	−2.7	−1.6	−0.2	2.7	7.5	10.0	6.6	−1.7	−2.6
				k = .17	−7.0	−8.1	−5.4	−2.0	2.0	1.5	0.8	5.3	7.6	6.2	1.5	−2.8
				P_g	18.5	18.0	17.3	16.5	15.5	15.5	16.7	16.0	14.5	13.7	15.5	18.0
				c	2.7	2.2	1.1	0.3	−0.7	−1.4	−0.7	−0.7	−2.3	−2.5	−0.5	2.7
				±.87	−4.3	−5.9	−4.3	−1.7	1.3	0.1	0.1	4.6	5.3	3.7	1.0	0.1

				28. ATLANTIC: Florida Current												
Miami Beach (US)	25°46N	80°08W	1931–46(1)	16	−5.4	−6.3	−8.5	−4.1	−1.3	−3.4	−5.4	−0.9	8.6	16.5	10.5	−0.3
Mayport (US)	30°24N	81°26W	1928–46(1)	19	−6.5	−7.5	−9.6	−5.7	−3.2	−3.4	−7.4	−1.1	13.6	21.3	10.6	−0.9
Fernandina (US)	30°41N	81°28W	1897–1924(2)	28	−9.9	−8.7	−8.4	−3.8	0.5	0.8	−6.8	−4.1	14.5	21.2	8.7	−4.4
Charleston (US)	32°47N	79°55W	1921–46(1)	26	−8.7	−8.1	−8.6	−3.3	−1.7	−1.7	−4.7	0.7	13.2	17.3	7.8	−2.5
				k = .11	−7.8	−7.7	−8.7	−4.2	−1.3	−1.8	−6.0	−1.4	12.6	19.1	9.3	−2.2
				P_g	20.0	20.0	17.0	17.0	17.0	15.0	17.0	17.0	17.0	17.0	20.0	20.0
				c	2.6	2.6	0.2	−0.8	−0.8	−3.5	−2.0	−1.3	−1.4	−0.8	2.4	3.1
				±.76	−5.2	−5.1	−8.5	−5.0	−2.1	−5.3	−8.0	−2.7	11.2	18.3	11.7	0.9
				29. ATLANTIC: Bermuda												
Ireland Island (Be)	32°19N	64°50W	1833–43(1)	11	1.0	1.0	−3.8	−5.7	−4.7	−3.8	−4.7	−1.1	2.3	10.5	5.6	3.5
St. Georges (Be)	32°22N	63°42W	1932–37(4)	6	0.7	−2.0	−4.1	−5.7	−2.3	−1.6	1.3	4.0	0.7	5.2	3.4	0.3
				k = .24	0.9	−0.2	−3.9	−5.7	−3.7	−2.9	−2.3	0.9	1.7	8.4	4.7	2.2
				P_g	20.0	20.0	20.0	18.5	19.0	20.0	21.5	20.0	18.0	18.0	18.0	18.5
				c	1.2	1.2	0.8	−0.7	−0.2	0.1	1.1	0.3	−1.8	−1.2	−1.0	0.2
				±1.13	2.1	1.0	−3.1	−6.4	−3.9	−2.8	−1.2	1.2	−0.1	7.2	3.7	2.4
				30. ATLANTIC: Gulf Stream												
Hampton Roads (US)	36°57N	76°20W	1927–46(3)	20	−7.0	−6.8	−5.2	−0.6	−0.5	2.0	0.2	4.1	10.9	8.4	1.0	−6.4
Baltimore (US)	39°16N	76°35W	1902–46(1)	45	−12.8	−13.2	−8.2	−0.9	4.5	8.6	8.5	10.1	10.6	6.1	−3.2	−10.4
Atlantic City (US)	39°21N	74°25W	1911–20(1), 1922–46	35	−8.5	−7.2	−5.6	−1.4	0.2	3.6	2.9	6.5	8.0	6.6	0.1	−5.7
Fort Hamilton (US)	40°37N	74°02W	1893–1920	28	−9.0	−12.4	−8.1	0.7	3.2	5.9	4.4	7.4	6.8	6.5	−0.5	−5.4
New York, W. St. (US)	40°42N	74°01W	1928–46	19	−9.2	−9.5	−4.9	0.2	1.4	5.5	5.4	6.7	8.1	5.1	−0.5	−7.8
New York, Pier (US)	40°42N	74°01W	1920–27	8	−11.2	−4.2	−5.4	−1.2	4.3	4.0	3.1	5.8	6.2	3.4	0.4	−5.4
Newport (US)	41°30N	71°20W	1930–46(2)	17	−5.5	−6.1	−4.6	−2.5	−0.9	4.0	4.3	4.7	5.4	4.6	0.9	−4.4
				k = .08	−9.3	−9.1	−6.3	−0.8	1.9	5.1	4.5	6.9	8.3	6.0	−0.5	−6.8
				P_g	20.0	18.0	18.0	18.0	18.0	17.0	18.0	17.0	17.0	20.0	20.0	20.0
				c	2.1	0.1	−0.3	−0.3	−0.3	−2.0	−1.5	−1.8	−1.9	1.7	1.9	2.6
				±.77	−7.2	−9.0	−6.6	−1.1	1.6	3.1	3.0	5.1	6.4	7.7	1.4	−4.2

Station	Latitude	Longitude	Years	Total Years	J	F	M	A	M	J	J	A	S	O	N	D
31. ATLANTIC: Gulf of Maine																
Boston (US)	42°21N	71°03W	1921–46(1)	26	−4.6	−3.5	−2.5	−0.3	0.7	3.4	1.8	1.8	2.0	2.6	1.3	−2.2
Portland (US)	43°40N	70°15W	1912–46(1)	35	−4.6	−3.8	−3.9	−0.4	1.5	3.7	2.8	1.8	1.4	2.0	0.8	−2.3
Eastport (US)	44°54N	66°59W	1929–46(1)	18	−1.6	−0.8	−1.1	0.1	0.1	1.6	1.6	−1.2	−0.7	0.9	0.9	−0.4
St. John (Ca)	45°15N	66°04W	1930–34, 1938, 1942, 1946	8	−1.5	−3.5	−1.8	3.5	6.4	3.6	0.9	−1.2	−2.5	0.1	−1.4	−2.7
				k = .11	−3.4	−3.0	−2.5	0.4	1.8	3.1	1.9	0.6	0.5	1.6	0.6	−1.9
				P_g	18.5	15.5	15.5	15.5	15.5	15.5	15.5	15.5	17.0	17.0	17.0	17.0
				c	2.7	0.7	−0.7	−0.7	−0.7	−1.4	−1.9	−1.2	0.2	0.8	1.0	1.7
				±.64	−0.7	−2.3	−3.2	−0.3	1.1	1.7	0.0	−0.6	0.7	2.4	1.6	−0.2
32. ATLANTIC: Gulf of St. Lawrence																
Father Point (Ca)	48°31N	68°28W	1938–39, 1942(1), 1945–46	5	−2.7	−4.5	−3.0	1.9	4.3	5.0	1.6	−1.1	−3.9	0.7	−1.4	3.1
Portage Island (Ca)	47°08N	65°03W	1917–19(3) (July–Oct. only)	3							3.6	2.1	−1.2	0.3		
Point Peter (Ca)	48°38N	64°10W	1924–25(1)	2	−5.4	−12.1	−16.1	−5.1	1.0	5.0	4.4	5.9	3.2	6.5	5.3	7.4
				k = .32	−3.6	−7.0	−7.4	−0.4	3.2	5.0	3.0	1.6	−1.4	1.7	0.8	4.5
				P_g	14.0	12.5	12.0	14.0	13.5	12.5	12.0	13.5	15.5	15.0	14.0	14.0
				c	1.0	−0.5	−1.4	0.6	0.1	−1.6	−2.6	−0.4	1.5	1.6	0.8	1.5
				±1.61	−2.6	−7.5	−8.8	0.2	3.3	3.4	0.4	1.2	0.1	3.3	1.6	6.0
33. ATLANTIC: Nova Scotia and Prince Edward Island																
Halifax (NS)	44°40N	63°34W	1922–25(1), 1927–28 (2), 1933, 1935–38, 1941–46	16	2.9	1.7	−0.3	−1.7	−3.5	−1.7	−4.7	−2.9	−2.2	3.0	4.5	5.4
Charlottetown (PEI)	46°13N	63°08W	1934, 1940, 1942, 1946	4	2.3	4.9	−2.9	−2.3	−4.3	−0.6	−1.8	−3.2	−3.7	2.1	3.2	6.3
St. Paul Island	47°12N	60°09W	1921–26(2)	6	0.0	−0.3	0.1	−2.4	−3.6	−1.4	−3.3	−1.4	−1.4	5.6	3.4	4.7
				k = .20	2.0	2.0	−0.8	−2.0	−3.7	−1.4	−3.6	−2.6	−2.4	3.4	3.9	5.4
				P_g	14.5	12.5	12.5	13.5	14.0	14.0	14.0	15.0	17.0	16.0	14.5	12.5
				c	0.8	−1.2	−1.6	−0.6	−0.1	−0.8	−1.3	0.4	2.3	1.9	0.6	−0.7
				±.57	2.8	0.8	−2.4	−2.6	−3.8	−2.2	−4.9	−2.2	−0.1	5.3	4.5	4.7

				34. ATLANTIC: Newfoundland												
Harrington (Ca)	50°31N	59°27W	1940–42, 1945–46	5	2.4	2.1	−4.6	−6.5	−3.4	0.2	−3.1	−1.9	−1.3	5.1	5.1	6.0
Port Aux Basques (Ne)	47°34N	59°07W	1935–37(2)	3	0.0	5.8	−2.8	−1.6	−3.4	−0.3	3.3	−2.5	−0.3	−2.5	1.5	2.7
St. John's (Ne)	47°34N	52°42W	1935–37(2)	3	12.4	10.2	1.7	−4.4	−8.1	−11.7	−6.2	−5.6	0.8	1.1	1.4	8.4
				k = .30	4.9	6.0	−1.9	−4.1	−5.0	−3.9	−2.0	−3.3	−0.3	1.2	2.7	5.7
				P_g	10.5	9.5	10.0	12.5	13.0	13.5	13.5	14.0	15.5	14.5	12.5	9.5
				c	−1.4	−2.4	−2.3	0.2	0.7	0.5	0.0	1.2	2.6	2.2	0.4	−1.9
				±1.85	3.5	3.6	−4.2	−3.9	−4.3	−3.4	−2.0	−2.1	2.3	3.4	3.1	3.8
				35. ATLANTIC: Hudson Bay												
Churchill (Ca)	58°47N	94°12W	1940–43	4	0.6	−8.3	−9.8	−11.3	−1.6	0.0	3.9	0.9	5.8	8.5	8.5	2.7
				k = .50												
				P_g	17.5	18.5	18.5	18.5	17.5	13.5	10.5	11.0	12.5	13.0	14.0	15.5
				c	2.9	3.9	3.5	3.5	2.5	−2.2	−5.7	−4.5	−3.1	−2.0	−0.8	1.4
					3.5	−4.4	−6.3	−7.8	0.9	−2.2	−1.8	−3.6	2.7	6.5	7.7	4.1
				36. ATLANTIC: Greenland, South												
Ivigtut (Gr)[5]	61°12N	48°11W	1944–49(2)	6	6.6	−1.2	−0.6	−11.6	−12.8	−4.7	−2.2	−2.1	0.1	6.3	7.1	15.1
				k = .41												
				P_g	97.0	2.0	5.0	9.8	11.4	11.0	9.3	9.5	8.0	5.0	3.0	99.0
				c	−8.3	−3.3	−0.7	4.1	5.7	4.6	2.4	3.3	1.7	−0.7	−2.5	−5.8
					−1.7	−4.5	−1.3	−7.5	−7.1	−0.1	0.2	1.2	1.8	5.6	4.6	9.3
				37. ATLANTIC: Iceland												
Reykjavik (Ic)[2]	64°09N	21°56W	1951	1	12.6	−1.0	−16.5	−15.8	−14.0	−8.5	−4.0	0.5	0.6	10.8	12.4	22.6
				k = 1.00												
				P_g	97.5	2.0	6.0	9.5	14.0	12.5	10.5	9.5	8.0	5.0	4.0	99.0
				c	−8.5	−4.0	−0.4	3.1	7.6	5.4	2.9	2.6	1.0	−1.4	−2.2	−6.5
					4.1	−5.0	−16.9	−12.7	−6.4	−3.1	−1.1	3.1	1.6	9.4	10.2	16.1
				38. ARCTIC OCEAN: Greenland, North												
Cape Sheridan	82°27N	61°21W	Dec. 1908–June 1909(2)	1	1.0	5.2	−14.0	−3.9	−6.7	10.4						8.0
				P_g	15.0	17.0	21.0	23.5	22.5	18.5						15.5
				c	−3.7	−1.7	1.9	4.4	3.4	−1.3						−2.7
					−2.7	3.5	−12.1	0.5	−3.3	9.1						5.3

Station	Latitude	Longitude	Years	Total Years	J	F	M	A	M	J	J	A	S	O	N	D
				39. ARCTIC OCEAN: Point Barrow												
Uglaamie (Al)[3]	71°15N	156°37W	Mar.–June, 1883				9.1	−3.0	−2.4	−3.6						
				P$_g$			22.0	19.0	17.5	16.0						
				e			3.6	0.6	−0.9	−3.1						
							12.7	−2.6	−3.3	−6.7						
				40. PACIFIC: Aleutian Islands												
Massacre Bay (Al)[5]	52°50N	186°48W	1943–52(6)	10	6.5	1.1	−2.4	−8.7	−4.3	−3.8	−0.6	0.1	−1.2	1.7	5.1	6.6
Constantine Harbor (Al)[5]	51°25N	180°43W	1944–47(4)	4	−2.9					−4.7	−2.1	0.3	−2.0	3.3	6.2	9.1
Sweeper Cove (Al)[5]	51°51N	176°39W	1943–52(1)	10	5.4	5.8	−0.5	−6.4	−2.8	−3.4	−5.3	−3.3	−2.1	1.2	5.0	6.4
Dutch Harbor (Al)[5]	53°54N	166°32W	1934–39 ,1946–52(1)	13	1.9	4.4	−2.6	−5.4	0.1	−3.3	−5.8	−7.3	−1.0	5.1	5.2	8.7
				k = .17	3.1	3.8	−1.9	−6.7	−2.1	−3.8	−3.9	−3.2	−1.5	3.0	5.3	7.7
				P$_g$	2.7	2.0	8.0	9.5	9.5	11.2	13.7	12.5	9.5	7.0	3.8	2.0
				c	−4.4	−5.1	0.5	2.0	2.0	3.0	5.0	4.5	1.4	−0.5	−3.5	−4.6
				±.93	−1.3	−1.3	−1.4	−4.7	−0.1	−0.8	1.1	1.3	−0.1	2.5	1.8	3.1
				41. PACIFIC: Alaska												
Seward (Al)	60°06N	149°27W	1925–38(2), 1944–46(2)	17	4.5	5.2	−1.6	−8.7	−9.7	−10.5	−7.5	−5.8	−1.9	11.2	12.6	11.9
Yakutat (Al)[5]	59°33N	139°44W	1940–52	13	10.4	2.5	−0.9	−6.6	−12.1	−11.4	−9.2	−7.5	−1.3	11.2	11.7	13.1
				k = .18	7.4	3.8	−1.2	−7.6	−10.9	−11.0	−8.4	−6.6	−1.6	11.2	12.2	12.5
				P$_g$	9.5	10.0	11.0	10.0	11.3	13.5	15.0	13.0	10.0	5.0	5.0	6.5
				c	0.0	0.5	1.1	0.1	1.4	2.9	3.9	2.6	−0.5	−4.9	−4.7	−2.5
				±.81	7.4	4.3	−0.1	−7.5	−9.5	−8.1	−4.5	−4.0	−2.1	6.3	7.5	10.0
				42. PACIFIC: Alaska and British Columbia												
Sitka (Al)[5]	57°03N	135°20W	1938–52	15	9.5	4.0	0.1	−4.5	−9.7	−10.7	−9.5	−9.6	−3.2	8.2	11.2	14.5
Ketchikan (Al)	55°20N	131°38W	1919–46	28	9.6	4.7	−1.2	−5.4	−7.3	−6.6	−7.6	−9.2	−5.5	4.7	10.5	13.5
Prince Rupert (BC)	54°19N	130°20W	1933, 1939, 1945–46	4	11.5	0.8	2.0	−9.3	−5.0	−5.3	−5.3	−12.0	−2.2	−0.1	8.1	16.7
				k = .16	9.9	3.7	0.2	−5.8	−7.8	−7.9	−7.9	−9.9	−4.1	5.1	10.3	14.4
				P$_g$	10.0	12.0	12.0	12.5	14.0	15.3	17.0	16.5	14.0	10.5	9.0	9.0
				c	−2.2	−0.2	−0.6	−0.1	1.4	2.0	3.2	3.4	0.8	−2.1	−3.4	−2.7
				±.92	7.7	3.5	−0.4	−5.9	−6.4	−5.9	−4.7	−6.5	−3.3	3.0	6.9	11.7

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43. PACIFIC: British Columbia and Washington

Canoe Pass (BC)	50°15N	125°25W	June 1945–May 1946(2)	1	5.7	11.8	3.8	−2.3	−5.3	−17.2	−2.3	−5.0	−5.9	−4.7	5.1	16.3
Pt. Atkinson (BC)	49°19N	123°15W	1927–33, 1939, 1946	9	6.1	−1.6	−1.8	−9.2	−1.6	0.0	−0.9	−0.6	2.7	−4.3	−1.2	12.5
Vancouver (BC)	49°18N	123°07W	1920–23(2), 1931, 1935, 1941, 1945–46	9	8.3	3.6	0.1	−8.9	−6.4	−2.0	−2.3	−3.2	−2.1	−0.7	1.7	12.0
Victoria (BC)	48°26N	123°23W	Apr. 1923–Mar. 1924 (2), 1932, 1936, Apr. 1940–Mar. 1941(2), 1945–46	6	8.0	8.4	0.1	−6.0	−3.6	−5.3	−3.8	−5.0	−3.0	−2.6	0.8	11.7
Clayoquot (BC)	49°09N	125°55W	1935, 1941, 1946	3	18.6	15.6	7.4	−3.9	−9.1	−10.0	−10.3	−11.8	−5.8	−5.4	0.4	14.4
Neah Bay (US)[5]	48°22N	124°37W	1934–52(2)	19	11.8	11.2	4.1	−3.9	−8.5	−9.7	−10.6	−10.3	−7.4	0.3	8.3	14.6
Seattle (US)	47°36N	122°20W	1899–1946	48	9.3	7.0	1.5	−3.5	−4.5	−4.5	−4.8	−4.9	−4.8	−3.1	3.9	8.6
Crescent City (US)[5]	41°45N	124°12W	1933–47, 1950–52(1)	18	5.6	7.6	−0.4	−7.9	−7.0	−6.9	−3.7	−2.2	0.9	0.0	3.9	10.1
				k = .11	9.1	7.3	1.5	−5.7	−5.7	−5.8	−5.0	−5.2	−3.1	−2.2	3.3	11.6
				P_g	17.0	17.0	16.5	17.0	17.0	16.5	17.5	17.0	16.3	17.5	17.0	17.0
				c	0.6	0.6	−0.3	0.2	0.2	−1.0	−0.5	−0.3	−1.1	0.7	0.4	1.1
				±1.09	9.7	7.9	1.2	−5.5	−5.5	−6.8	−5.5	−5.5	−4.2	−1.5	3.7	12.7

44. PACIFIC: California Current

San Francisco (US)	37°48N	122°28W	1897–1946(1)	50	1.8	1.4	−1.4	−5.4	−5.0	−2.3	1.5	2.4	4.1	2.1	−0.1	1.2
Los Angeles (US)	33°43N	118°16W	1923–46(1)	24	−1.7	−3.0	−6.1	−7.4	−5.4	−1.8	3.6	5.7	7.3	4.9	2.1	1.6
La Jolla (US)	32°52N	117°15W	1924–46(1)	23	−1.8	−3.2	−6.1	−7.3	−5.8	−1.9	3.2	5.9	7.7	4.8	2.4	1.8
San Diego (US)	32°42N	117°14W	1916–25	10	−0.8	−4.2	−5.7	−7.2	−5.7	−1.1	4.0	5.0	6.5	5.9	2.2	1.5
				k = .10	−0.4	−1.7	−4.4	−6.6	−5.4	−1.9	2.8	4.5	6.2	4.0	1.4	1.5
				P_g	19.5	18.5	17.5	15.5	14.5	12.5	12.5	13.3	12.8	15.5	18.0	19.5
				c	4.2	3.2	1.8	−0.2	−1.2	−3.9	−4.4	−2.9	−3.5	−0.2	2.5	4.7
				±.69	3.8	1.5	−2.6	−6.8	−6.6	−5.8	−1.6	1.6	2.7	3.8	3.9	6.2

45. PACIFIC: Mexico

Guaymas (Me)[5]	27°51N	110°54W	1942–44(2)	3	−17.1	−15.6	−13.1	−9.5	−0.9	13.2	18.7	17.8	20.2	8.8	−9.6	−12.8
La Paz (Me)[5]	24°10N	110°19W	1950(1)	1								5.9	11.1	7.1	1.0	−4.7
Acapulco (Me)[5]	16°51N	99°55W	1949–50(2)	2	−1.8	−10.4	−13.7	−10.2	1.2	11.4	12.2	7.9	6.4	0.0	0.1	−3.1
Salina Cruz (Me)[5]	16°10N	95°12W	1941–44(2)	4	−20.1	−20.4	−9.1	−1.2	6.5	12.9	10.4	16.2	15.0	1.9	−6.1	−5.7
				k = .33	−15.2	−16.5	−11.6	−6.3	2.5	12.7	14.1	13.6	14.8	4.8	−5.0	−7.5
				P_g	15.2	15.9	14.2	13.5	12.8	11.8	11.8	10.8	12.2	13.5	15.2	17.6
				c	2.0	2.7	0.6	−0.1	−0.8	−2.5	−3.0	−3.3	−2.0	−0.1	1.8	4.9
				±2.06	−13.2	−13.8	−11.0	−6.4	1.7	10.2	11.1	10.3	12.8	4.7	−3.2	−2.6

Station	Latitude	Longitude	Years	Total Years	J	F	M	A	M	J	J	A	S	O	N	D
46. PACIFIC: Central America																
San Jose (Gu)[5]	13°55N	90°50W	1949–50(1)	2	3.9	−3.2	−16.0	−9.2	−4.1	5.4	4.2	10.3	−1.6	3.2	3.4	3.7
La Union (ES)[5]	13°20N	87°49W	1948–50(1)	3	0.7	−4.5	−5.1	−6.8	0.8	3.4	4.7	2.7	2.8	3.1	−0.7	−1.0
San Juan del Sur (Ni)[5]	11°15N	85°53W	1949–50(2)	2	−8.8	−14.2	−8.1	−7.5	5.3	9.2	7.1	7.7	5.7	4.4	0.7	−1.4
Puntarenas (CR)[5]	9°58N	84°50W	1941–50(1)	10	1.4	−4.9	−7.5	−6.2	−0.1	2.0	4.0	4.5	1.8	0.9	0.4	3.7
Balboa (CZ)	8°58N	79°34W	1909–46	38	−8.1	−17.7	−17.5	−11.3	2.5	7.0	6.4	5.1	8.0	10.9	9.2	6.1
Naos Island (CZ)[5]	8°55N	79°32W	1949–50(1)	2	−9.9	−19.7	−17.5	−15.1	3.2	9.3	7.0	7.3	9.9	12.7	11.3	1.4
Buenaventura (Co)[5]	3°54N	77°6W	1941–46, 1948–50(1)	9	−1.8	−12.7	−13.4	−6.4	3.6	6.0	4.0	2.9	3.8	5.0	5.7	4.2
				k = .14	−3.7	−12.0	−12.9	−8.9	1.8	5.7	5.3	4.9	5.0	6.4	5.1	3.6
				P_g	13.9	13.2	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.8	13.9
				c	1.6	0.9	−0.2	−0.2	−0.2	−0.9	−1.4	−0.7	−0.8	−0.2	0.3	2.1
				±1.35	−2.1	−11.1	−13.1	−9.1	1.6	4.8	3.9	4.2	4.2	6.2	5.4	5.7
47. PACIFIC: Central South America																
La Libertad (Ec)[5]	2°12S	80°55W	1948–50(3)	3	−1.9	−0.6	0.9	−2.8	2.4	5.3	2.1	−3.4	−3.7	−1.7	0.8	2.6
Talara (Pe)[5]	4°35S	81°17W	1942–50	9	3.8	6.2	4.2	2.7	2.3	2.5	−0.2	−3.4	−4.9	−4.9	−4.6	−3.7
Callao (Pe)[5]	12°03S	77°09W	1942–50	9	2.2	5.1	4.7	3.2	3.4	2.0	−0.6	−3.6	−5.1	−5.5	−3.2	−2.5
Matarani (Pe)[5]	17°00S	72°07W	1941–50(2)	10	3.6	3.2	3.9	2.4	3.6	0.1	−2.1	−4.1	−4.9	−4.0	−1.9	0.2
Valparaiso (Ch)[5]	33°01S	71°38W	1941–47(2)	7	3.4	2.5	3.0	2.4	−0.4	2.5	−1.0	−1.0	−4.5	−5.0	−3.1	1.2
				k = .17	2.5	3.6	3.5	1.9	2.2	2.3	−0.5	−3.1	−4.7	−4.4	−2.6	−0.6
				P_g	12.5	13.2	13.9	14.5	15.9	16.2	16.2	16.9	16.6	16.6	15.2	13.9
				c	−2.1	−1.4	−1.1	−0.5	0.9	0.5	0.0	1.4	1.0	1.6	0.4	−0.2
				±.71	0.4	2.2	2.4	1.4	3.1	2.8	−0.5	−1.7	−3.7	−2.8	−2.2	−0.8
48. PACIFIC: Gulf de Ancud																
Puerto Montt (Ch)[5]	41°29S	72°58W	1942–46(4)	5	−1.2	−4.4	−1.8	−1.5	2.0	2.2	2.3	2.0	2.4	−4.2	0.6	1.5
				k = .45												
				P_g	12.2	12.8	12.5	13.9	11.5	13.9	14.9	13.5	14.5	15.2	14.2	11.5
				c	−0.7	−0.1	−0.8	0.6	−1.8	−0.1	0.4	−0.3	0.6	1.9	1.1	−0.9
					−1.9	−4.5	−2.6	−0.9	0.2	2.1	2.7	1.7	3.0	−2.3	1.7	0.6

				49. PACIFIC: Hawaii												
Honolulu (TH)	21°18N 157°52W	1905–46	42	−1.3	−1.9	−2.1	−3.2	−2.9	−2.2	−0.1	2.4	4.7	4.1	2.0	0.6
			k = .15												
			P_g	17.0	17.2	17.6	18.5	18.5	18.1	17.5	16.5	16.5	16.5	16.6	17.0
			c	0.2	0.4	0.4	1.3	1.3	0.2	−0.9	−1.2	−1.3	−0.7	−0.4	0.7
				−1.1	−1.5	−1.7	−1.9	−1.6	−2.0	−1.0	1.2	3.4	3.4	1.6	1.3
			50.	PACIFIC: Johnston Island											
Johnston Island[5,9]	16°45N 169°31W	1947–51(3)	5	−4.6	−4.1	−7.1	1.0	−4.3	−5.0	−2.4	5.6	11.0	4.8	0.5	4.6
			k = .58												
			P_g	14.5	14.5	15.5	15.5	15.0	15.0	14.5	13.5	13.5	13.5	14.2	14.0
			c	0.6	0.6	1.2	1.2	0.7	0.0	−1.0	−1.3	−1.4	−0.8	0.1	0.6
				−4.0	−3.5	−5.9	2.2	−3.6	−5.0	−3.4	4.3	9.6	4.0	0.6	5.2
			51.	PACIFIC: Palmyra Island											
Palmyra Island[5,10]	5°53N 162°05W	1947–49(3)	3												
			k = .58	−2.1	−2.1	−7.1	−9.4	−8.5	−11.8	−8.1	8.6	8.3	12.4	12.4	7.7
			P_g	11.8	10.8	11.8	14.2	14.2	13.2	13.5	13.5	13.5	12.5	12.2	11.8
			c	−0.5	−1.5	−0.9	1.5	1.5	−0.2	−0.4	0.3	0.2	−0.2	−0.3	0.0
				−2.6	−3.6	−8.0	−7.9	−7.0	−12.0	−8.5	8.9	8.5	12.2	12.1	7.7
				52. PACIFIC: Samoa											
Pago Pago (Sa)[5]	14°17S 170°41W	1949–51	3	−2.2	2.3	4.0	3.4	3.4	−1.6	−2.8	−3.5	−2.0	−0.9	−0.9	0.7
			k = .58												
			P_g	11.8	9.8	11.8	13.5	13.5	14.2	14.5	14.9	13.5	12.2	12.2	11.8
			c	−0.5	−2.5	−0.9	0.8	0.8	0.8	0.6	1.7	0.2	−0.5	−0.3	0.0
				−2.7	−0.2	3.1	4.2	4.2	−0.8	−2.2	−1.8	−1.8	−1.4	−1.2	0.7
				53. PACIFIC: Guam											
Apra Harbor (Gu)[5]	13°26N 144°39E	1949–51	3	−6.5	−4.4	0.1	2.9	4.6	5.7	5.9	4.3	2.8	−2.2	−7.3	−5.9
			k = .58												
			P_g	12.2	11.5	12.5	11.8	11.8	11.2	10.8	8.8	9.1	9.1	11.5	12.2
			c	1.6	0.9	1.5	0.8	0.8	−0.5	−1.4	−2.7	−2.5	−1.9	0.7	2.1
				−4.9	−3.5	1.6	3.7	5.4	5.2	4.5	1.6	0.3	−4.1	−6.6	−3.8

Station	Latitude	Longitude	Years	Total Years	J	F	M	A	M	J	J	A	S	O	N	D
54. PACIFIC: Marshall Islands																
Kwajalein (MI)[5]	8°44N	167°44E	1946–51(3)	6	−6.0	−1.0	1.5	2.7	1.4	−0.4	0.2	0.8	2.4	1.3	−0.9	−2.1
				k = .41												
				P_g	11.8	9.8	11.8	12.5	12.5	12.5	12.5	12.5	12.5	9.1	11.8	11.2
				c	0.6	−1.4	0.2	0.9	0.9	0.2	−0.3	0.4	0.3	−2.5	0.4	0.5
					−5.4	−2.4	1.7	3.6	2.3	−0.2	−0.1	1.2	2.7	−1.2	−0.5	−1.6
55. PACIFIC: Solomon Islands, New Britain, New Guinea																
Guadalcanal (SI)[5]	9°25S	159°59E	1947–49(3)	3	−3.5	−2.1	2.6	8.5	9.5	0.5	−5.0	−3.8	−2.3	−1.4	−0.3	−2.9
Rabaul (NB)[5, 11]	4°13S	152°12E	1948–50(3)	2		3.0	7.8	7.6	3.9	0.0	−5.8	−4.9	−0.3			
Dregor Harbor (NG)[5]	6°39S	147°52E	July 1948–Oct. 1949(2)	2	−3.6	−2.4	−2.1	4.9	4.9	−0.9	−0.6	0.2	1.4	0.3	0.3	−2.7
Port Moresby (NG)	9°26S	147°06E	July 1939–June 1940(2)	1	−0.1	3.4	9.7	10.3	9.8	11.3	−4.7	−12.2	−5.2	−9.7	−6.4	−5.7
				k = .37	−2.7	0.0	4.1	8.0	7.5	2.3	−4.2	−4.9	−1.7	−3.1	−1.7	−3.6
				P_g	9.5	9.1	10.8	11.5	12.2	12.5	12.8	12.5	12.5	11.8	11.5	9.1
				c	−1.3	−1.7	−0.4	0.3	1.0	0.6	0.4	0.8	0.7	0.6	0.5	−1.2
				±1.37	−4.0	−1.7	3.7	8.3	8.5	2.9	−3.8	−4.1	−1.0	−2.5	−1.2	−4.8
56a. PACIFIC OCEAN; Banda Sea																
Amboina (NEI)	3°42S	128°12E	1929–31(1)	3	1.0	4.6	6.9	5.2	−0.5	−2.7	−6.7	−8.6	−7.0	−1.1	4.0	5.1
				k = .58												
				P_g	8.5	9.1	9.1	9.1	10.1	10.8	11.8	10.8	11.5	11.2	9.1	9.1
				c	−1.0	−0.4	−0.8	−0.8	0.2	0.2	0.7	0.4	1.0	1.3	−0.6	0.1
					0.0	4.2	6.1	4.4	−0.3	−2.5	−6.0	−8.2	−6.0	0.2	3.4	5.2
56b. PACIFIC OCEAN: Celebes Island, South																
Makassar (NEI)[12]	5°06S	119°24E	1925–31(1)	7	8.7	9.6	9.9	6.4	−1.8	−6.1	−8.9	−10.7	−6.9	−5.0	1.0	4.0
				k = .38												
				P_g	8.5	9.1	9.1	9.1	10.1	10.8	11.8	10.8	11.5	11.2	9.1	9.1
				c	−1.0	−0.4	−0.8	−0.8	0.2	0.2	0.7	0.4	1.0	1.3	−0.6	0.1
					7.7	9.2	9.1	5.6	−1.6	−5.9	−8.2	−10.3	−5.9	−3.7	0.4	4.1

				56c. PACIFIC OCEAN: Java, East												
Djamoeanrif (NEI)	6°58S	112°45E	1925–31(1)	7	2.1	0.8	0.5	−4.0	−9.3	−5.2	1.3	3.4	4.6	3.0	−0.3	2.8
Sembilangan (NEI)	7°06S	112°42E	1925–31	7	2.4	3.1	1.0	−4.4	−10.2	−6.2	0.4	2.8	4.6	3.3	0.2	3.0
Soerabaja (NEI)	7°12S	112°36E	1925–31(1)	7	1.2	3.4	1.5	−4.3	−9.8	−6.1	0.1	2.2	4.5	4.2	0.5	2.7
				k = .21	1.9	2.4	1.0	−4.2	−9.8	−5.8	0.6	2.8	4.6	3.5	0.1	2.8
				P_g	8.5	9.1	9.1	9.1	10.1	10.8	11.8	10.8	11.5	11.2	9.1	9.1
				c	−1.0	−0.4	−0.8	−0.8	0.2	0.2	0.7	0.4	1.0	1.3	−0.6	0.1
				±.28	0.9	2.0	0.2	−5.0	−9.6	−5.6	1.3	3.2	5.6	4.7	−0.4	2.9
				56d. PACIFIC OCEAN: Java Sea, South												
Toeban (NEI)	6°53S	112°03E	1929–31(1)	3	−7.4	−3.9	−2.0	3.2	12.3	8.5	1.1	−1.8	−4.9	−1.8	0.1	−4.0
Semarang (NEI)	7°00S	110°24E	1925–31	7	−2.6	−3.8	−3.8	2.3	8.3	6.6	−0.1	−1.3	−2.2	−1.8	−0.3	−2.4
Pekalongan (NEI)	6°52S	109°40E	1926–31	6	−4.0	−4.5	−2.2	2.8	9.8	7.9	0.9	−1.9	−3.0	−2.2	−1.1	−2.6
Tegal (NEI)	6°51S	109°07E	1926–31	6	−9.7	−7.0	−3.3	2.8	10.8	11.5	4.4	2.1	0.1	−1.3	−3.1	−7.9
Cheribon (NEI)	6°43S	108°34E	1925–31(2)	7	−6.1	−6.3	−4.4	3.1	9.8	8.5	0.9	0.2	−2.1	−0.6	0.6	−3.9
Tandjong-Priok (NEI)	6°06S	106°54E	1925–31(1)	7	−6.8	−5.9	−5.7	0.7	9.3	5.5	1.0	0.7	2.3	1.2	1.5	−3.7
Batavia (NEI)	6°10S	106°40E	1927–31(2)	5	−8.1	−8.5	−8.3	2.5	9.7	8.1	1.0	3.4	2.1	1.6	1.2	−4.9
				k = .16	−6.2	−5.6	−4.3	2.4	9.8	7.9	1.2	0.1	−1.0	−0.6	0.0	−4.0
				P_g	8.5	9.1	9.1	9.1	10.1	10.8	11.8	10.8	11.5	11.2	9.1	9.1
				c	−1.0	−0.4	−0.8	−0.8	0.2	0.2	0.7	0.4	1.0	1.3	−0.6	0.1
				±.62	−7.2	−6.0	−5.1	1.6	10.0	8.1	2.6	0.5	0.0	0.7	−0.6	−3.9
				56. PACIFIC OCEAN: Sunda Islands Summary												
				k = .12	−1.9	−1.2	−0.7	1.0	2.4	1.9	−0.5	−0.7	−0.4	0.1	0.4	−0.6
				c	−1.0	−0.4	−0.8	−0.8	0.2	0.2	0.7	0.4	1.0	1.3	−0.6	0.1
				±1.42	−2.9	−1.6	−1.5	0.2	2.6	2.1	0.2	−0.3	0.6	1.4	−0.2	−0.5
				57a. PACIFIC OCEAN: Borneo, South												
Bandjermasin (NEI)	3°18S	114°36E	1927–31	5	14.0	10.8	8.7	4.8	1.7	−7.3	−13.1	−18.7	−18.7	−8.5	4.6	22.2
S. Moesangketjil (NEI)	3°30S	114°30E	1930–31(1)	2	5.6	5.5	4.5	−0.3	2.6	−1.7	−5.6	−11.9	−11.8	−3.9	4.5	12.4
				k = .39	11.2	9.0	7.3	3.1	2.0	−5.4	−10.6	−16.4	−16.4	−7.0	4.6	18.9
				P_g	10.8	10.8	10.8	9.1	9.1	9.8	10.1	9.1	10.8	10.5	9.8	10.8
				c	1.2	1.2	0.8	−0.9	−0.9	−0.9	−1.1	−1.4	0.2	0.5	0.0	1.7
				±2.02	12.4	10.2	8.1	2.2	1.1	−6.3	−11.7	−17.8	−16.2	−6.5	4.6	20.6

(498)

Station	Latitude	Longitude	Years	Total Years	J	F	M	A	M	J	J	A	S	O	N	D
57b. PACIFIC OCEAN: Karimata Strait																
Oepang (NEI)[21]	2°45S	104°58E	1928–31(3)	4	29.7	25.9	29.0	16.8	3.0	−20.7	−35.7	−33.8	−26.1	−14.6	5.9	20.8
Soengsang (NEI)	2°20S	104°45E	1928–31	4	12.7	9.3	4.8	0.8	−1.1	−4.6	−13.0	−15.2	−13.5	0.5	6.5	13.0
				k = .35	21.2	17.6	16.9	8.8	1.0	−12.6	−24.3	−24.5	−19.8	−7.0	6.2	16.9
				P_g	10.8	10.8	10.8	9.1	9.1	9.8	10.1	9.1	10.8	10.5	9.8	10.8
				c	1.2	1.2	0.8	−0.9	−0.9	−0.9	−1.1	−1.4	0.2	0.5	0.0	1.7
				±5.58	22.4	18.8	17.7	7.9	0.1	−13.5	−25.4	−25.9	−19.6	−6.5	6.2	18.6
57c. PACIFIC OCEAN: Sumatra, East																
Tambilahan (NEI)[21]	0°20S	103°09E	1928–30	3	11.9	4.6	12.4	−3.2	−4.5	−9.9	−12.3	−13.8	−8.6	1.6	11.0	11.0
Prigi-Radja (NEI)	0°15S	103°15E	1929–31(1	3	5.1	4.3	4.5	−6.2	−7.6	−3.6	−7.4	−7.5	−2.9	3.5	9.7	7.7
				k = .41	8.5	4.4	8.4	−4.7	−6.0	−6.8	−9.8	−10.6	−5.8	2.6	10.4	9.4
				P_g	10.8	10.8	10.8	9.1	9.1	9.8	10.1	9.1	10.8	10.5	9.8	10.8
				c	1.2	1.2	0.8	−0.9	−0.9	−0.9	−1.1	−1.4	0.2	0.5	0.0	1.7
				±1.71	9.7	6.0	7.6	−3.6	−13.3	−14.8	−16.3	−12.2	−5.1	3.8	26.9	11.5
57d. PACIFIC OCEAN: Singapore																
Johore Bahru (Ma)	1°27N	103°46E	Dec. 1923–Nov. 1924 (2), Feb. 1929–Jan. 1930(2)	2	8.5	4.8	6.8	−2.7	−12.4	−13.9	−15.2	−10.8	−5.3	3.3	26.9	9.8
				k = .71												
				P_g	10.8	10.8	10.8	9.1	9.1	9.8	10.1	9.1	10.8	10.5	9.8	10.8
				c	1.2	1.2	0.8	−0.9	−0.9	−0.9	−1.1	−1.4	0.2	0.5	0.0	1.7
					9.7	6.0	7.6	−3.6	−13.3	−14.8	−16.3	−12.2	−5.1	3.8	26.9	11.5
57e. PACIFIC OCEAN: Gulf of Siam																
Prachuap Kirikhan (Si)	11°48N	99°49E	1910–15(2), 1940–45	12	15.9	13.9	7.5	−0.5	−9.3	−20.1	−22.5	−18.7	−12.9	6.5	19.5	20.3
Bangkok Bar (Si)	13°29N	100°34E	1926–45	19	8.4	11.7	8.9	−0.6	−8.6	−15.0	−13.8	−11.5	−9.2	3.6	13.0	13.1
Fort Phrachula Chomklao (Si)	13°33N	100°35E	1940–45	6	5.8	9.9	6.4	−1.5	−3.0	−12.7	−12.3	−7.6	−7.8	3.4	9.6	9.7
Ko̧ Sichang (Si)	13°09N	100°49E	1940–46	7	12.0	14.9	8.8	1.0	−7.7	−16.9	−14.0	−9.2	−7.5	−2.1	8.2	11.9
				k = .16	10.7	12.8	8.1	−0.3	−7.6	−16.4	−15.8	−12.1	−9.5	2.9	12.9	14.0
				P_g	10.8	10.8	10.8	9.1	9.1	9.8	10.1	9.1	10.8	10.5	9.8	10.8
				c	1.2	1.2	0.8	−0.9	−0.9	−0.9	−1.1	−1.4	0.2	0.5	0.0	1.7
				±1.50	11.9	14.0	8.9	−1.2	−8.5	−17.3	−16.9	−13.5	−9.3	3.4	12.9	15.7

57. PACIFIC OCEAN: Karimata Strait and Gulf of Siam, Summary																
			k = .13	12.1	11.4	9.5	0.8	−4.9	−12.7	−15.5	−14.4	−11.3	−0.1	10.9	14.2
			c	1.2	1.2	0.8	−0.9	−0.9	−0.9	−1.1	−1.4	0.2	0.5	0.0	1.7
			±1.79	13.3	12.6	10.3	−0.1	−5.8	−13.6	−16.6	−15.8	−11.1	0.4	10.9	15.9
58a. PACIFIC OCEAN: Celebes Sea, South																
Menado (NEI)	1°32N	124°50E	1927–31	5	1.6	−0.8	3.1	4.1	1.4	−0.3	0.8	−3.4	−5.0	−2.2	−0.9	1.6
				k = .45												
				P_g	10.8	10.1	10.8	10.5	10.1	10.8	10.5	9.8	9.8	11.2	9.5	10.8
				c	0.8	0.8	0.8	0.1	0.1	−0.6	−1.1	−1.8	−1.2	0.8	−0.4	1.7
					2.4	0.0	3.9	4.2	1.5	−0.9	−0.3	−5.2	−6.2	−1.4	−1.3	3.3
58b. PACIFIC OCEAN: Celebes Sea, North																
Zamboanga (PI)	6°54N	122°04E	1922–23(1), 1927(1)	3	6.1	1.2	4.3	0.9	0.6	0.6	−4.0	−2.7	−2.1	0.0	−1.8	−2.7
				k = .58												
				P_g	10.8	10.1	10.8	10.5	10.1	10.8	10.5	9.8	9.8	11.2	9.5	10.8
				c	0.8	0.8	0.8	0.1	0.1	−0.6	−1.1	−1.8	−1.2	0.8	−0.4	1.7
					6.9	2.0	5.1	1.0	0.7	0.0	−5.1	−4.5	−3.3	0.8	−2.2	−1.0
58c. PACIFIC OCEAN: Sulu Archipelago																
Jolo (PI)	6°04N	121°00E	1924–27(3), 1930(1)	5	−4.6	−3.4	4.6	1.5	1.2	0.6	0.9	−0.6	−0.3	0.9	1.2	−3.4
				k = .45												
				P_g	10.8	10.1	10.8	10.5	10.1	10.8	10.5	9.8	9.8	11.2	9.5	10.8
				c	0.8	0.8	0.8	0.1	0.1	−0.6	−1.1	−1.8	−1.2	0.8	−0.4	1.7
					−3.8	−2.6	5.4	1.6	1.3	0.0	−0.2	−2.4	−1.5	1.7	0.8	−1.7
58. PACIFIC OCEAN: Celebes Sea Summary																
				k = .28	1.0	−1.0	4.0	2.2	1.1	0.3	−0.8	−2.2	−2.5	−0.4	−0.5	−1.5
				c	0.8	0.8	0.8	0.1	0.1	−0.6	−1.1	−1.8	−1.2	0.8	−0.4	1.7
				±1.10	1.8	−0.2	4.8	2.3	1.2	−0.3	−1.9	−4.0	−3.7	0.4	−0.9	0.2
59a. PACIFIC OCEAN: Luzon																
Manila (PI)	14°35N	120°58E	1901–20(1), 1926–34 (2), 1935–38	30	−12.0	−12.5	−9.5	−5.0	−0.9	3.4	10.0	13.9	12.5	7.2	−0.6	−6.5
				k = .18												
				P_g	13.2	12.8	12.5	10.5	10.5	9.8	9.5	7.8	9.1	11.5	11.8	12.2
				c	2.8	2.4	1.7	−0.3	−0.3	−1.7	−2.5	−3.5	−2.3	0.7	1.2	2.3
					−9.2	−10.1	−7.8	−5.3	−1.2	1.7	7.5	10.4	10.2	7.9	0.6	−4.2

59b. PACIFIC OCEAN: San Bernardino Strait

Station	Latitude	Longitude	Years	Total Years	J	F	M	A	M	J	J	A	S	O	N	D
Port San Miguel (PI)	12°40N	123°35E	1914–15(2)	2	−10.1	−9.8	−8.2	−5.2	1.2	3.4	7.9	11.6	11.9	6.1	−2.7	−6.4
Biri Island (PI)	12°39N	124°22E	1926–27(2)	2	−7.9	−6.1	1.2	3.4	3.1	1.2	6.1	4.6	3.4	5.5	−6.7	−7.9
Batuan Bay (PI)	12°25N	123°47E	1926–27(2)	2	−11.6	−9.2	−2.1	3.1	5.2	3.7	2.7	5.8	6.7	7.6	−3.1	−8.8
				k = .41	−9.9	−8.4	−3.0	0.4	3.2	2.8	5.6	7.3	7.3	6.4	−4.2	−7.7
				P_g	13.2	12.8	12.5	10.5	10.5	9.8	9.5	7.8	9.1	11.5	11.8	12.2
				c	2.8	2.4	1.7	−0.3	−0.3	−1.7	−2.5	−3.5	−2.3	0.7	1.2	2.3
				±1.41	−7.1	−6.0	−1.3	0.1	2.9	1.1	3.1	3.8	5.0	7.1	−3.0	−5.4

59c. PACIFIC OCEAN: Sebu

Station	Latitude	Longitude	Years	Total Years	J	F	M	A	M	J	J	A	S	O	N	D
Oloilo (PI)	10°42N	122°34E	1903–09(4)	7	−9.8	−9.2	−6.1	−1.2	1.8	4.0	7.3	7.0	5.8	4.0	0.9	−4.6
Sebu (PI)	10°18N	123°54E	1935–40(1)	6	−9.4	−10.3	−6.4	−2.7	1.6	4.9	7.1	8.0	7.7	4.3	0.3	−5.2
				k = .28	−9.6	−9.6	−6.2	−1.8	1.7	4.4	7.2	7.4	6.6	4.1	0.7	−4.8
				P_g	13.2	12.8	12.5	10.5	10.5	9.8	9.5	7.8	9.1	11.5	11.8	12.2
				c	2.8	2.4	1.7	−0.3	−0.3	−1.7	−2.5	−3.5	−2.3	0.7	1.2	2.3
				±.32	−6.8	−7.2	−4.5	−2.1	1.4	2.7	4.7	3.9	4.3	4.8	1.9	−2.5

59. PACIFIC OCEAN: Philippine Islands, East, Summary

	J	F	M	A	M	J	J	A	S	O	N	D
k = .17	−10.6	−10.4	−6.7	−2.5	1.0	3.6	7.9	9.8	9.0	5.8	−0.9	−6.1
c	2.8	2.4	1.7	−0.3	−0.3	−1.7	−2.5	−3.5	−2.3	0.7	1.2	2.3
±.92	−7.8	−8.0	−5.0	−2.8	0.7	1.9	5.4	6.3	6.7	6.5	0.3	−3.8

60. PACIFIC: Philippine Islands, West

Station	Latitude	Longitude	Years	Total Years	J	F	M	A	M	J	J	A	S	O	N	D
Puerto Princesa (PI)	9°44N	118°43E	1916–18(1)	3	6.5	−4.4	−4.8	−5.4	−6.6	−6.9	−4.2	−2.3	11.4	6.2	6.8	3.8
Araceli (PI)	10°35N	119°59E	1913–15(3)	3	−4.2	−6.6	−5.7	−4.5	−4.2	−3.0	−1.4	5.6	11.4	10.5	1.3	1.0
Port Uson (PI)	12°01N	120°12E	1912–16(2)	5	−3.9	−6.9	−7.2	−6.6	−4.5	−2.3	3.5	5.9	7.4	6.8	4.1	3.2
				k = .30	−0.5	−6.0	−5.9	−5.5	−5.1	−4.1	−0.7	3.1	10.1	7.8	4.1	2.7
				P_g	12.5	11.8	11.8	10.8	10.1	9.8	9.8	8.5	9.1	11.5	10.8	11.8
				c	2.3	1.6	1.2	0.2	−0.5	−1.5	−2.0	−2.6	−2.1	0.9	0.4	2.1
				±1.41	1.8	−4.4	−4.7	−5.3	−5.6	−5.6	−2.7	0.5	8.0	8.7	4.5	4.8

61. PACIFIC: South China Sea

Macao (Ch)	22°12N	113°33E	1937–46	10	−2.8	−4.3	−4.6	−8.1	−5.3	−5.2	−2.8	1.1	7.9	14.0	7.8	2.0
Hong Kong (Ch)	22°18N	114°10E	May 1929–Apr. 1930(2)	1	−1.0	−8.5	−5.9	−8.4	−5.3	−14.2	−1.7	−0.5	12.7	23.3	12.7	−3.1
				k = .34	−2.4	−5.4	−4.9	−8.2	−5.3	−7.5	−2.5	0.7	9.1	16.3	9.0	0.7
				P_g	22.0	21.0	18.3	13.5	9.1	7.1	5.4	6.8	9.8	15.2	19.3	21.0
				c	8.5	7.5	4.4	−0.4	−4.8	−7.5	−9.7	−7.6	−4.7	1.3	5.6	8.0
				±1.45	6.1	2.1	−0.5	−8.6	−10.1	−15.0	−12.2	−6.9	4.4	17.6	14.6	8.7

62. PACIFIC: Formosa

Takao (Fo)	22°37N	120°16E	1904–43(1)	40	−12.6	−11.4	−6.7	−4.3	−0.4	4.7	10.4	12.9	10.7	7.1	−0.2	−9.9
Kirun (Fo)	25°09N	121°45E	1904–24(3)	21	−13.2	−12.3	−10.0	−6.0	1.9	8.9	14.7	17.8	14.4	3.3	−5.6	−13.5
				k = .14	−12.9	−11.8	−8.2	−5.1	0.6	6.6	12.4	15.1	12.4	5.4	−2.7	−11.4
				P_g	20.6	20.0	17.6	13.9	9.8	7.8	6.1	6.8	9.1	13.5	19.3	20.3
				c	7.3	6.7	3.9	0.2	−3.9	−6.6	−8.8	−7.4	−5.2	−0.2	5.8	7.5
				±1.25	−5.6	−5.1	−4.3	−4.9	−3.3	0.0	3.6	7.7	7.2	5.2	3.1	−3.9

63. PACIFIC: China

Yang-tsi-Kiang (Ch)	30°49N	122°38E	1923	1	−14.5	−13.6	−17.1	−9.0	0.9	6.3	10.0	10.3	25.7	11.9	0.5	−11.4
Shanghai (Ch)	31°24N	121°30E	1930	1	−36.9	−18.4	−14.9	−4.8	2.7	17.8	23.9	13.5	21.9	12.5	−5.8	−11.5
				k = .70	−25.7	−16.0	−16.0	−6.9	1.8	12.1	16.9	11.9	23.8	12.2	−2.7	−11.5
				P_g	26.5	24.5	21.0	15.0	11.7	7.0	5.8	6.3	12.5	19.5	23.7	26.0
				c	10.4	8.4	4.5	−1.5	−4.8	−10.2	−11.9	−10.7	−4.6	3.0	7.4	10.4
				±3.13	−15.3	−7.6	−11.5	−8.4	−3.0	1.9	5.0	1.2	19.2	15.2	4.7	−1.1

64. PACIFIC: China, Yellow Sea

Newchwang (Ch)	40°38N	122°10E	Feb. 1924–Jan. 1925(2)	1	−11.7	−28.5	−17.3	−7.4	4.2	16.4	31.3	27.1	14.7	3.9	−13.0	−19.7
				k = 1.00												
				P_g	29.4	26.5	21.5	15.0	10.0	5.4	5.0	7.0	15.0	20.5	24.7	27.6
				c	12.6	9.7	4.3	−2.2	−7.2	−12.5	−13.4	−10.7	−2.8	3.3	7.7	11.3
					0.9	−18.8	−13.0	−9.6	−3.0	3.9	17.9	16.4	11.9	7.2	−5.3	−8.4

65. PACIFIC: Korea

Genzan (Ko)[12, 13]	39°10N	127°27E	1932–44	13	−12.9	−13.2	−10.7	−7.1	0.8	9.1	13.5	17.5	14.3	2.2	−5.3	−8.3
				k = .28												
				P_g	25.8	23.4	19.8	14.5	10.8	6.5	6.5	8.0	14.0	19.5	22.8	24.5
				c	10.0	7.6	3.6	−1.7	−5.4	−10.4	−10.9	−8.7	−2.8	3.3	6.8	9.2
					−2.9	−5.6	−7.1	−8.8	−4.6	−1.3	2.6	8.8	11.5	5.5	1.5	0.9

Station	Latitude	Longitude	Years	Total Years	J	F	M	A	M	J	J	A	S	O	N	D
66. PACIFIC: Japan, Oyashio																
Hanasaki (Ja)	43°17N	145°35E	1900–24(1)	25	4.7	−0.5	−3.0	−6.5	−3.5	−1.9	0.0	2.9	2.5	−0.6	−0.2	6.4
Honto (Ja)^{13}	46°41N	141°51E	1922–44(1)	23	2.2	−3.0	−4.7	−5.0	−2.2	−0.3	3.0	3.4	0.1	−1.3	1.9	5.4
				k = .14	3.4	−1.8	−3.8	−5.8	−2.8	−1.1	1.5	3.2	1.3	−1.0	0.8	5.9
				P_g	13.0	13.5	13.5	13.0	11.0	9.5	9.5	11.0	13.5	15.0	13.5	12.5
				c	1.1	1.6	1.2	0.7	−1.3	−3.5	−4.0	−1.8	0.6	2.7	1.4	1.1
				±.67	4.5	−0.2	−2.6	−5.1	−4.1	−4.6	−2.5	1.4	1.9	1.7	2.2	7.0
67. PACIFIC: Japan, North Kuroshio																
Wazima (Ja)^{13}	37°24N	136°54E	1900–49	50	−5.3	−11.5	−14.5	−15.4	−5.9	2.7	10.3	15.1	12.8	6.7	4.5	1.0
Iwasaki (Ja)	40°35N	139°55E	1900–24	25	−6.2	−11.3	−14.5	−11.9	−4.8	2.2	9.0	14.8	10.5	5.4	4.9	1.5
Osyoro (Ja)^{13}	43°13N	140°52E	1930–49(2)	20	−4.9	−8.5	−10.5	−7.7	−1.8	2.4	8.1	10.7	8.3	3.4	1.8	−1.2
Otaru (Ja)	43°13N	141°03E	1906–33	28	−5.8	−9.7	−10.0	−8.6	−2.4	3.2	8.2	12.2	8.4	3.6	2.1	−0.8
				k = .09	−5.6	−10.5	−12.7	−11.5	−4.0	2.6	9.1	13.5	10.3	5.0	3.5	0.3
				P_g	17.5	17.0	16.0	14.3	12.0	9.5	9.5	10.0	13.0	17.0	18.0	17.0
				c	3.7	3.2	2.8	0.1	−2.2	−5.4	−5.9	−4.7	−1.8	2.8	4.0	3.7
				±.81	−1.9	−7.3	−9.9	−11.4	−6.2	−2.8	3.2	8.8	8.5	7.8	7.5	4.0
68. PACIFIC: Japan, China Sea																
Hukabori (Ja)	32°41N	129°49E	1900–24	25	−15.3	−16.9	−13.3	−9.0	−2.2	5.8	12.5	21.6	18.5	10.2	0.0	−11.6
Hamada (Ja)	34°55N	132°04E	1900–24	25	−13.1	−16.6	−16.7	−13.7	−3.8	6.6	15.0	21.4	15.6	9.4	2.4	−6.2
				k = .14	−14.2	−16.8	−15.0	−11.4	−3.0	6.2	13.8	21.5	17.1	9.8	1.2	−8.9
				P_g	23.0	21.0	19.4	15.5	12.0	8.5	8.5	8.2	12.5	18.2	21.5	22.5
				c	7.6	5.6	3.6	−0.3	−3.8	−8.0	−8.5	−8.1	−3.9	2.8	5.9	7.6
				±.98	−6.6	−11.2	−11.4	−11.7	−6.8	−1.8	5.3	13.4	13.2	12.6	7.1	−1.3

				69. PACIFIC: Japan, Kuroshio												
Hososima (Ja)[13]	32°25N	131°40E	1900–49	50	−12.7	−12.7	−11.4	−8.6	−4.0	5.3	8.3	14.5	13.4	10.7	5.1	−7.5
Osaki Wan (Ja)[14]	34°08N	135°08E	1926–33(2)	8	−14.2	−15.8	−15.1	−9.0	−2.9	6.9	10.4	16.9	9.7	12.6	3.5	−3.6
Kusimoto (Ja)	33°28N	136°47E	1900–24	25	−10.9	−11.7	−12.2	−9.1	−2.4	4.9	8.4	14.3	13.7	11.1	1.1	−6.6
Aburatubo (Ja)[13]	35°09N	139°37E	1900–45(1), 1947–49(2)	49	−4.2	−6.3	−9.2	−8.5	−3.4	1.4	3.6	6.6	9.0	7.6	3.5	0.2
Aikawa (Ja)	38°18N	141°30E	1900–24(2)	25	−3.1	−7.3	−11.5	−11.8	−5.4	0.3	5.4	9.9	10.5	7.5	4.2	1.7
				k = .08	−8.6	−10.2	−11.4	−9.3	−3.7	3.5	6.8	11.8	11.4	9.6	3.6	−3.2
				P_g	19.0	18.0	17.5	15.0	12.0	9.5	9.5	9.0	12.0	17.0	20.0	20.0
				c	4.6	3.6	2.7	0.2	−2.8	−6.0	−6.5	−6.3	−3.4	2.2	5.4	6.1
				±1.18	−4.0	−6.6	−8.7	−9.1	−6.5	−2.5	0.3	5.5	8.0	11.8	9.0	2.9
				70. PACIFIC: New Zealand, North												
Auckland (NZ)	36°51S	174°49E	Sept. 1917–Aug. 1919 (2), 1921–23, 1937, 1941	7	1.5	0.3	3.1	1.5	3.6	5.2	0.0	−2.4	−4.6	−2.7	−4.6	−0.6
Wellington (NZ)	41°17S	174°48E	Sept. 1918–Aug. 1919 (2), 1921–24, 1927, 1930, 1937, 1939, 1942	10	1.8	−0.3	1.2	0.2	1.5	3.6	0.2	−1.6	−3.4	−1.9	−1.6	0.2
				k = .24	1.6	0.0	2.2	0.8	2.6	4.4	0.1	−2.0	−4.0	−2.3	−3.1	−0.2
				P_g	11.8	14.2	15.9	15.9	13.9	10.8	11.5	11.2	13.9	12.8	12.5	10.8
				c	−0.6	1.8	3.1	3.1	1.1	−2.7	−2.5	−2.1	0.5	0.0	−0.1	−1.1
				±.51	1.0	1.8	5.3	3.9	3.7	1.7	−2.4	−4.1	−3.5	−2.3	−3.2	−1.3
				71. PACIFIC: New Zealand, South												
Port Lyttelton (NZ)	43°36S	172°51E	1923–27	5	2.1	7.6	4.2	3.9	4.2	2.1	−2.2	−2.5	−4.0	−3.7	−3.4	−7.7
Dunedin (NZ)	45°53S	170°33E	1923–27, 1937	6	3.4	3.7	1.2	1.9	2.7	−1.8	0.0	−2.1	−3.3	−3.0	−1.8	−1.5
Bluff (NZ)	46°35S	168°22E	1917–22(3)	5	−5.0	1.1	5.9	3.2	1.3	−2.3	−2.0	−2.3	−3.8	2.3	−0.5	2.3
				k = .25	0.2	4.1	3.8	3.0	2.7	−0.7	−1.4	−2.3	−3.7	−1.5	−1.9	−2.3
				P_g	6.8	10.1	12.5	15.9	8.8	7.1	7.8	5.4	9.8	10.1	5.7	4.4
				c	−1.4	1.9	3.9	7.3	0.2	−2.2	−2.0	−3.7	0.6	1.5	−2.7	−3.3
				±1.26	−1.2	6.0	7.7	10.3	2.9	−2.9	−3.4	−6.0	−3.1	0.0	−4.6	−5.6

72. PACIFIC: Australia, East Coast

Station	Latitude	Longitude	Years	Total Years	J	F	M	A	M	J	J	A	S	O	N	D
Ballina (Au)	28°52S	153°37E	1928–38(5)	11	1.3	0.4	−1.1	8.4	9.3	4.4	−0.8	−2.9	−5.7	−5.1	−2.9	−5.1
Yamba (Au	29°36S	153°21E	1928–36(9)	9	−2.0	3.2	1.9	5.3	8.9	10.5	5.9	1.6	−6.9	−11.2	−7.5	−10.0
				k = .24	−0.4	1.8	0.4	6.8	9.1	7.4	2.6	−0.6	−6.3	−8.2	−5.2	−7.6
				P_g	11.2	12.5	14.9	16.2	16.6	16.9	18.3	17.9	16.9	15.9	12.8	10.5
				c	−3.4	−2.1	−0.1	1.2	1.6	1.2	2.1	2.4	1.3	0.9	−2.0	−3.6
				±1.53	−3.8	−0.3	0.3	8.0	10.7	8.6	4.7	1.8	−5.0	−7.3	−7.2	−11.2

73. PACIFIC: Australia, Southeast Coast

Station	Latitude	Longitude	Years	Total Years	J	F	M	A	M	J	J	A	S	O	N	D
Newcastle (Au)	32°55S	151°48E	1928–38	11	−1.1	−0.2	0.6	4.3	2.6	5.9	1.3	−3.1	−1.9	−4.0	−4.5	−0.3
Sydney (Au)	33°51S	151°14E	1897–1927, 1934, 1937–38	33	0.7	−1.6	1.3	4.4	5.1	2.7	−0.4	−3.8	−3.6	−2.4	−2.5	−0.3
Williamstown (Au)	37°52S	144°55E	1928–39(1), 1943–44(2)	13	−0.3	−2.3	−2.8	3.9	3.0	3.6	1.3	1.1	−1.4	−1.9	−3.9	−0.6
				k = .14	0.0	−1.5	−0.1	4.2	3.9	3.7	0.5	−2.1	−2.5	−2.6	−3.4	−0.4
				P_g	12.5	14.2	15.9	18.6	15.6	15.2	19.3	14.5	14.5	13.9	12.5	10.8
				c	−1.8	−0.1	1.2	3.0	0.9	−0.2	3.4	−0.7	−0.8	−0.8	−2.0	−3.0
				±.65	−1.8	−1.6	1.1	8.1	4.8	3.5	3.9	−2.8	−3.3	−3.4	−5.4	−3.4

74. INDIAN OCEAN: Australia, South, I

Station	Latitude	Longitude	Years	Total Years	J	F	M	A	M	J	J	A	S	O	N	D
Port Phillip Heads (Au)	38°18S	144°37E	1927–29(2), 1931	3	−2.7	−10.4	−9.1	0.9	4.6	6.9	11.3	3.7	7.0	1.7	−5.5	−8.1
Beachport (Au)	37°30S	140°00E	1927–31	5	−4.3	−9.6	−6.0	3.2	4.9	6.3	8.1	5.2	5.6	−1.8	−6.2	−5.3
Robe (Au)	37°09S	139°45E	July 1945–June 1946(2)	1	4.1	−7.7	−2.7	−7.0	9.9	0.5	−6.3	13.1	5.6	−4.8	1.8	−6.6
Port Adelaide (Au)	34°51S	138°30E	1882–91, 1933–37, 1941–45	21	−1.9	−8.0	−4.3	−0.9	5.5	9.4	6.0	3.9	1.2	−2.2	−6.4	−2.2
Second Valley (Au)	35°31S	138°10E	1938–42(1)	5	−7.1	−7.2	−4.3	−2.0	8.5	14.2	6.1	11.1	4.5	−9.6	−6.6	−7.0
				k = .19	−2.8	−8.5	−5.2	−0.6	6.1	8.5	6.3	6.0	3.8	−2.9	−5.6	−4.9
				P_g	12.5	14.2	16.6	19.3	15.9	16.2	19.3	16.6	15.9	15.2	12.8	11.5
				c	−2.5	−0.8	1.2	3.9	0.5	0.1	2.7	0.7	−0.1	−0.2	−2.4	−3.0
				±1.24	−5.3	−9.3	−3.0	3.3	6.6	8.6	9.0	6.7	3.7	−3.1	−8.0	−7.9

75. INDIAN OCEAN: Australia, South, II

Stenhouse Bay (Au)	35°15S	136°58E	1942–46(1)	5	−5.5	−5.8	−3.6	−0.6	8.5	9.1	7.9	4.3	3.4	−5.5	−5.8	−5.8
Port Wallaroo (Au)	33°56S	137°38E	1933–37	5	0.5	−4.5	−3.2	2.6	6.9	4.8	4.1	2.5	0.1	−2.8	−7.3	−3.9
Port Pirie (Au)	33°09S	138°01E	1933–37(1), 1941–45	10	0.8	−4.0	−1.0	0.0	4.8	3.6	5.0	−0.6	−0.6	−4.4	−3.4	−0.4
Whyalla (Au)	33°01S	137°34E	1943–46(1)	4	9.1	0.9	−0.6	0.0	3.6	1.5	−0.6	−6.7	−3.3	−6.1	1.2	1.8
				k = .21	1.2	−3.4	−2.0	0.4	5.8	4.7	4.2	−0.2	−0.2	−4.7	−3.8	−1.9
				P_g	11.5	13.5	16.2	19.3	16.2	16.6	19.6	17.2	16.6	15.9	12.8	12.2
				c	−3.6	−1.6	0.7	3.8	0.7	0.4	2.9	1.2	0.5	0.4	−2.5	−2.4
				±1.37	−2.4	−5.0	−1.3	4.2	6.5	5.1	7.1	1.0	0.3	−4.3	−6.3	−4.3

76. INDIAN OCEAN: Australia, Southwest

Franklyn Harbour (Au)	33°41S	136°56E	1935–39	5	−2.5	−1.7	−3.3	1.8	7.8	6.1	0.0	5.7	−5.2	−3.1	−4.5	−1.7
Port Lincoln (Au)	34°49S	135°52E	1920–24	5	−9.2	−7.3	−8.2	−5.5	2.4	11.3	11.6	4.9	−0.6	0.9	−1.5	0.0
Thevenard (Au)	32°09S	133°39E	1934–36, 1940–42	6	−6.7	−5.2	−0.9	0.9	7.6	6.4	8.8	5.5	4.3	−9.2	−6.1	−5.2
Albany (Au)	35°02S	117°54E	Oct. 1923–Sept. 1924(2)	1	−7.6	−7.2	−3.6	7.5	20.5	15.0	9.8	5.8	−3.3	−8.8	−14.1	−14.2
Fremantle (Au)	32°03S	115°44E	1937–38	2	−11.5	−5.7	−1.4	5.0	14.3	12.2	6.4	3.0	−1.7	−6.9	−9.0	−4.8
				k = .24	−7.0	−5.2	−3.7	0.9	8.8	9.4	7.1	5.1	−1.0	−4.8	−5.9	−4.1
				P_g	12.5	13.5	15.9	17.6	16.2	16.6	19.3	16.6	16.9	15.9	13.5	12.5
				c	−2.6	−1.6	0.4	2.1	0.7	0.4	2.6	0.6	0.8	0.4	−1.8	−2.1
				±1.65	−9.6	−6.8	−3.3	3.0	9.5	9.8	9.7	5.7	−0.2	−4.4	−7.7	−6.2

77. INDIAN OCEAN: Australia, West

Port Hedland (Au)	20°18S	118°35E	1913, 1927, 1932–33, 1938(1)	5	−0.7	5.4	17.6	14.5	8.4	−0.7	−6.8	−14.5	−9.9	−7.5	−4.4	−1.1
				k = .45												
				P_g	7.4	8.8	9.8	12.8	13.9	15.9	16.6	16.6	14.5	13.2	10.1	9.1
				c	−4.5	−3.1	−2.5	0.5	1.6	2.9	3.1	3.8	1.6	0.9	−2.0	−2.3
					−5.2	2.3	15.1	15.0	10.0	2.2	−3.7	−10.7	−8.3	−6.6	−6.4	−3.4

78. INDIAN OCEAN: Java, South

Patjitan (NEI)	8°12S	111°05E	1928–31	4	2.8	4.7	6.8	3.8	7.2	−1.8	−10.2	−8.8	−14.4	−0.4	3.3	6.9
Tjilatjap (NEI)	7°44S	109°00E	1925–31	7	6.6	4.1	7.8	6.3	9.9	−4.6	−10.8	−13.2	−16.5	−5.1	6.0	9.1
				k = .30	5.1	4.3	7.4	5.3	8.8	−3.5	−10.6	−11.4	−15.7	−3.2	4.9	8.2
				P_g	8.8	9.1	9.1	9.1	10.1	11.5	12.5	11.2	11.8	11.5	9.1	9.1
				c	−0.9	−0.6	−1.0	−1.0	0.0	0.7	1.2	0.6	1.1	1.4	−0.8	−0.1
				±.98	4.2	3.7	6.4	4.3	8.8	−2.8	−9.4	−10.8	−14.6	−1.8	4.1	8.1

79a. INDIAN OCEAN: Java, Southwest

Station	Latitude	Longitude	Years	Total Years	J	F	M	A	M	J	J	A	S	O	N	D
Plaboean-Ratoe (NEI	7°00S	106°30E	1928-31(1)	4	−0.3	−0.3	1.6	1.5	13.9	0.2	−14.3	−7.8	−10.1	−1.1	7.7	8.7
				k = .50												
				P_g	9.1	9.1	9.1	9.1	9.1	10.8	11.8	10.5	11.5	11.5	9.1	9.1
				c	−0.4	−0.4	−0.8	−0.8	−0.8	0.2	0.7	0.1	1.0	1.6	−0.6	0.1
					−0.7	−0.7	0.8	0.7	13.1	0.4	−13.6	−7.7	−9.1	0.5	7.1	8.8

79b. INDIAN OCEAN: Sumatra, South

Station	Latitude	Longitude	Years	Total Years	J	F	M	A	M	J	J	A	S	O	N	D
Oosthaven (NEI)	5°27S	105°16E	1930-31(1)	2	−5.1	−10.2	−5.2	0.3	9.7	2.7	−0.6	−7.3	−7.7	1.0	13.6	9.8
Kroë (NEI)	5°11S	103°55E	1929-31(1)	3	−10.2	−8.1	−3.9	−3.5	13.8	5.1	−2.9	−6.8	−4.6	10.3	10.6	−0.1
				k = .45	−8.5	−8.8	−4.3	−2.2	12.4	4.3	−2.1	−7.0	−5.6	7.2	11.6	3.2
				P_g	9.1	9.1	9.1	9.1	9.1	10.8	11.8	10.5	11.5	11.5	9.1	9.1
				c	−0.4	−0.4	−0.8	−0.8	−0.8	0.2	0.7	0.1	1.0	1.6	−0.6	0.1
				±1.61	−8.9	−9.2	−5.1	−3.0	11.6	4.5	−1.4	−6.9	−4.6	8.8	11.0	3.3

79c. INDIAN OCEAN: Sumatra, West

Station	Latitude	Longitude	Years	Total Years	J	F	M	A	M	J	J	A	S	O	N	D
Benkoelen (NEI)	3°47S	102°15E	1925-31	7	−2.7	−9.5	−5.6	−0.3	9.7	0.0	0.5	−2.5	−2.3	4.3	6.9	1.6
Emmahaven (NEI)	0°58S	100°20E	1925-31	7	−6.0	−10.3	−6.0	−1.7	8.4	2.4	1.7	0.1	−0.7	4.8	6.7	1.1
Sibolga (NEI)	1°44N	98°46E	1930-31	2	−7.7	−7.9	−4.3	−2.5	12.0	5.4	−3.0	−3.5	−4.3	4.3	8.0	3.0
				k = .26	−4.8	−9.6	−5.6	−1.2	9.5	1.8	0.8	−1.5	−1.9	4.5	7.0	1.6
				P_g	9.1	9.1	9.1	9.1	9.1	10.8	11.8	10.5	11.5	11.5	9.1	9.1
				c	−0.4	−0.4	−0.8	−0.8	−0.8	0.2	0.7	0.1	1.0	1.6	−0.6	0.1
				±.66	−5.2	−10.0	−6.4	−2.0	8.7	2.0	1.5	−1.4	−0.9	6.1	6.4	1.7

79d. INDIAN OCEAN: Sumatra, North

Station	Latitude	Longitude	Years	Total Years	J	F	M	A	M	J	J	A	S	O	N	D
Belawan (NEI)	3°55N	98°43E	1925-31	7	−9.2	−14.9	−10.2	−1.9	9.3	7.8	5.9	5.3	1.6	5.8	3.4	−3.3
				k = .38												
				P_g	9.1	9.1	9.1	9.1	9.1	10.8	11.8	10.5	11.5	11.5	9.1	9.1
				c	−0.4	−0.4	−0.8	−0.8	−0.8	0.2	0.7	0.1	1.0	1.6	−0.6	0.1
					−9.6	−15.3	−11.0	−2.7	8.5	8.0	6.6	5.4	2.6	7.4	2.8	−3.2

79. INDIAN OCEAN: Java, Southwest, and Sumatra, West, Summary

	J	F	M	A	M	J	J	A	S	O	N	D
k = .18	−5.8	−9.3	−5.2	−1.2	10.6	3.3	−0.9	−2.1	−3.0	4.6	7.3	1.9
c	−0.4	−0.4	−0.8	−0.8	−0.8	0.2	0.7	0.1	1.0	1.6	−0.6	0.1
±1.38	−6.2	−9.7	−6.0	−2.0	9.8	3.5	−0.2	−2.0	−2.0	6.2	6.7	2.0

80a. INDIAN OCEAN: Malacca Strait

Bengkalis (NEI)	1°28N	102°08E	1929–31(1)	3	−4.2	−7.8	−8.5	−6.2	4.0	0.4	−0.9	−0.3	−0.6	7.7	12.2	4.2
				k = .58												
				P_g	10.5	10.5	9.8	9.1	8.8	9.5	10.1	9.1	10.1	10.8	9.1	10.1
				c	1.2	1.2	0.1	−0.6	−0.9	−0.9	−0.8	−1.1	−0.2	1.1	−0.4	1.3
					−3.0	−6.6	−8.4	−6.8	3.1	−0.5	−1.7	−1.4	−0.8	8.8	11.8	5.5

80b. INDIAN OCEAN: Malay Peninsula, West

Bass Harbour (Ma)	6°18N	99°47E	1934	1	−4.5	−11.2	−9.1	0.8	2.9	−1.4	5.6	4.7	4.1	5.7	14.3	−12.1
Ko Ta-Phao Noi (Si)	7°50N	98°26E	1940–46(1)	7	−12.0	−14.7	−11.2	−2.4	6.7	8.1	9.0	2.5	3.6	3.9	5.6	1.4
				k = .39	−10.1	−13.8	−10.7	−1.6	5.8	5.7	8.2	3.0	3.7	4.4	7.8	−2.0
				P_g	10.5	10.5	9.8	9.1	8.8	9.5	10.1	9.1	10.1	10.8	9.1	10.1
				c	1.2	1.2	0.1	−0.6	−0.9	−0.9	−0.8	−1.1	−0.2	1.1	−0.4	1.3
				±1.91	−8.9	−12.4	−10.6	−2.2	4.9	4.8	7.4	1.9	3.5	5.5	7.4	−0.7

80. INDIAN OCEAN: Malacca Strait Summary

				k = .32	−8.2	−11.8	−9.9	−3.1	5.2	3.9	5.1	1.9	2.3	5.5	9.3	0.1
				c	1.2	1.2	0.1	−0.6	−0.9	−0.9	−0.8	−1.1	−0.2	1.1	−0.4	1.3
				±1.88	−7.0	−10.6	−9.8	−3.7	4.3	3.0	4.3	0.8	2.1	6.6	8.9	1.4

81a. INDIAN OCEAN: Burma

Rangoon (Bu)	16°46N	96°10E	1937–41	5	−40.9	−37.9	−34.8	−22.6	−4.4	20.0	32.2	47.5	38.3	26.1	−1.3	−22.6
Akyab (Bu)	20°08N	92°54E	1937–41	5	−33.0	−36.1	−30.0	−11.7	12.7	34.0	34.0	27.9	15.8	6.6	−5.6	−14.7
Chittagong (In)	22°20N	91°50E	1937–46(2)	10	−54.9	−54.9	−42.7	−24.4	9.1	45.7	60.9	64.0	42.6	9.1	−18.3	−36.6
				k = .23	−44.6	−44.7	−36.8	−20.3	6.3	35.0	45.0	49.0	33.7	13.2	−9.8	−26.3
				P_g	14.9	13.2	11.8	7.1	6.1	2.4	3.0	4.7	5.7	9.1	11.8	14.9
				c	6.7	5.0	3.2	−1.5	−2.5	−6.9	−6.8	−4.4	−3.5	0.5	3.4	7.2
				±5.64	−37.9	−39.7	−33.6	−21.8	3.8	28.1	38.2	44.6	30.2	13.7	−6.4	−19.1

81b. INDIAN OCEAN: Kidderpore

Kidderpore (In)[21]	22°32N	88°20E	1881–93(1), 1937–46	23	−60.6	−66.2	−54.8	−41.0	−21.3	−3.0	44.1	97.6	104.3	52.7	−10.5	−41.7
				k = .21												
				P_a	14.9	13.2	11.8	7.1	6.1	2.4	3.0	4.7	5.7	9.1	11.8	14.9
				c	6.7	5.0	3.2	−1.5	−2.5	−6.9	−6.8	−4.4	−3.5	0.5	3.4	7.2
					−53.9	−61.2	−51.6	−42.5	−23.8	−9.9	37.3	93.2	100.8	53.2	−7.1	−34.5

Station	Latitude	Longitude	Years	Total Years	J	F	M	A	M	J	J	A	S	O	N	D
81. INDIAN OCEAN: Bay of Bengal, East, Summary																
				k = .16	−51.3	−53.6	−44.3	−28.9	−5.2	19.2	44.6	69.2	63.1	29.6	−10.1	−32.7
				c	6.7	5.0	3.2	−1.5	−2.5	−6.9	−6.8	−4.4	−3.5	0.5	3.4	7.2
				±2.81	−44.6	−48.6	−41.1	−30.4	−7.7	12.3	37.8	64.8	59.6	30.1	−6.7	−25.5
82. INDIAN OCEAN: Bay of Bengal, West																
Dublat (In)	21°38N	88°08E	1937–43(1)	7	−19.0	−28.2	−28.2	−19.0	5.4	17.5	17.5	20.6	20.6	14.5	5.4	−6.8
Vizagapatam (In)	17°41N	83°17E	1937–46(1)	10	−8.1	−20.3	−23.3	−14.2	−2.0	4.1	1.0	1.0	7.1	22.4	22.4	10.2
				k = .24	−13.6	−24.3	−25.8	−16.6	1.7	10.8	9.3	10.8	13.9	18.5	13.9	1.7
				P_g	14.9	13.5	11.8	6.1	5.4	1.4	1.7	2.4	5.1	9.1	13.2	15.2
				c	7.1	5.7	3.6	−2.1	−2.8	−7.5	−7.7	−6.3	−3.7	0.9	5.2	7.9
				±4.50	−6.5	−18.6	−22.2	−18.7	−1.1	3.3	1.6	4.5	10.2	19.4	19.1	9.6
83. INDIAN OCEAN: Arabian Sea																
Bombay (In)	18°55N	72°50E	1878–1946	69	3.4	−0.1	1.4	1.5	−3.0	4.0	−1.7	−1.0	−6.4	−4.7	1.2	5.4
Karāchi (In)	24°48N	66°58E	1937–46	10	−2.3	−3.5	−1.3	1.7	4.1	8.4	1.7	1.1	−4.4	−5.3	−0.4	−0.1
				k = .12	1.8	−1.0	0.7	1.6	−1.1	5.2	−0.8	−0.4	−5.9	−4.9	0.8	3.9
				P_g	15.9	14.5	11.5	8.5	5.7	1.4	0.0	2.4	5.1	11.5	13.9	15.6
				c	7.6	6.2	2.8	−0.2	−3.0	−8.0	−10.0	−6.8	−4.2	2.8	5.4	7.8
				±1.20	9.4	5.2	3.5	1.4	−4.1	−2.8	−10.8	−7.2	−10.1	−2.1	6.2	11.7
84. INDIAN OCEAN: Iran, Persian Gulf																
Fao (Ir)	29°58N	48°30E	1945	1	−9.1	−17.4	−12.4	0.8	9.8	16.0	17.1	8.8	3.1	−6.0	−3.8	−6.9
Basrah (Ir)	30°31N	47°51E	1917–18	2	−31.4	−7.9	7.3	34.2	54.4	41.0	20.1	−5.4	−22.8	−30.0	−30.7	−28.5
				k = .58	−20.3	−12.7	−2.6	17.5	32.1	28.5	18.6	1.7	−9.9	−18.0	−17.3	−17.7
				P_g	20.0	18.3	15.2	11.5	8.8	4.0	1.4	2.4	7.4	13.2	17.6	18.3
				c	9.0	7.3	3.8	0.1	−2.6	−8.1	−11.2	−9.5	−4.6	1.8	6.4	7.8
				±8.75	−11.3	−5.4	1.2	17.6	29.5	20.4	7.4	−7.8	−14.5	−16.2	−10.9	−9.9

				85. INDIAN OCEAN: Suez Canal												
Généffé (Su)	30°10N	32°34E	1937–41	5	5.7	4.6	−3.0	4.1	−1.1	−6.0	−2.3	−3.0	−7.0	−1.2	7.0	2.7
Kabret (Su)	30°16N	32°30E	1923–27, 1932–41	15	4.3	2.0	−0.7	−0.5	−0.8	−5.5	−2.3	−2.8	−6.7	−2.2	7.8	7.0
Déversoir (Su)	30°25N	32°21E	1937–41	5	5.0	4.5	−3.5	3.0	−1.2	−6.3	−1.3	−1.9	−5.6	−1.3	5.8	3.3
				k = .21	4.8	3.3	−2.0	1.5	−1.0	−5.8	−2.0	−2.6	−6.5	−1.7	7.1	5.0
				P_g	17.6	15.9	12.5	11.5	10.8	8.5	7.4	6.8	10.8	11.8	14.9	15.9
				c	6.1	4.4	0.6	−0.4	−1.1	−4.1	−5.7	−5.6	−1.7	−0.1	3.2	4.9
				±.62	10.9	7.7	−1.4	1.1	−2.1	−9.9	−7.7	−8.2	−8.2	−1.8	10.3	9.9
				86. INDIAN OCEAN: Gulf of Suez												
Port Thewfik (Su)	29°57N	32°34E	1923–29, 1931–46	23	11.2	7.9	4.1	4.6	3.7	−7.3	−11.4	−13.3	−17.7	−5.9	11.1	12.4
				k = .21												
				P_g	17.6	15.9	12.5	11.5	10.8	8.5	7.4	6.8	10.8	11.8	14.9	15.9
				c	6.1	4.4	0.6	−0.4	−1.1	−4.1	−5.7	−5.6	−1.7	−0.1	3.2	4.9
					17.3	12.3	4.7	4.2	2.6	−11.4	−17.1	−18.9	−19.4	−6.0	14.3	17.3
				87. INDIAN OCEAN: Arabia, Red Sea												
Aden (Ar)	12°47N	44°59E	1879–93(1), 1937–46(4)	25	5.3	6.8	7.4	9.5	10.4	4.4	−5.9	−13.8	−12.5	−9.6	−3.3	1.4
				k = .20												
				P_g	14.9	12.8	11.2	9.8	8.1	4.7	4.0	4.7	7.1	9.8	12.5	14.5
				c	5.9	3.8	1.8	0.4	−1.3	−5.4	−6.6	−5.2	−2.9	0.4	3.3	6.0
					11.2	10.6	9.2	9.9	9.1	−1.0	−12.5	−19.0	−15.4	−9.2	0.0	7.4
				88. INDIAN OCEAN: Kenya, Tanganyika												
Kilindini (Ke)	4°04S	39°39E	Oct. 1932–Sept. 1933(2)	1	1.6	0.5	4.1	5.0	1.7	−1.8	−0.6	−2.5	−4.0	−2.1	1.1	−3.2
Dar-es-Salaam (Ta)	6°49S	39°19E	Apr. 1929–Mar. 1930(2)	1	0.8	2.7	0.9	4.8	−1.3	−0.9	−4.2	−6.5	−2.3	2.4	−0.9	4.7
				k = .70	1.2	1.6	2.5	4.9	0.2	−1.4	−2.4	−4.5	−3.2	0.2	0.1	0.8
				P_g	9.8	9.8	10.1	11.5	11.8	14.2	14.2	14.2	14.2	12.5	11.8	10.1
				c	−1.7	−1.7	−1.8	−0.4	−0.1	1.6	1.1	1.8	1.7	0.6	0.1	−0.9
				±1.22	−0.5	−0.1	0.7	4.5	0.1	0.2	−1.3	−2.7	−1.5	0.8	0.2	−0.1
				89. INDIAN OCEAN: Union of South Africa												
Durban (SA)	29°52S	31°03E	Oct. 1926–Sept. 1927 (2)	1	5.7	0.5	8.9	3.8	1.3	−7.0	−14.9	−0.8	−8.9	1.8	1.4	8.2
				k = 1.00												
				P_g	12.5	12.5	14.2	16.9	17.6	21.6	22.0	21.3	19.3	15.9	14.5	12.5
				c	−3.7	−3.7	−2.4	0.3	1.0	4.3	4.2	4.2	2.1	−0.7	−1.9	−3.2
					2.0	−3.2	6.5	3.5	2.3	−2.7	−10.7	3.4	−6.8	1.1	−0.5	5.0

Station	Latitude	Longitude	Years	Total Years	J	F	M	A	M	J	J	A	S	O	N	D
90. ANTARCTIC OCEAN: Palmer Peninsula																
Marguerite Bay[15,17]	68°11S	67°00W	Apr. 1947–Feb. 1948	1	–3.5	3.2		11.1	2.1	–6.3	–0.8	–3.2	–0.2	–1.1	1.9	–2.9
Port Circoncision[16,17]	65°10S	64°14W	Feb.–Aug., Oct., Nov. 1909	1		–2.3	4.2	5.8	7.2	7.2	–1.0	3.4		–6.1	–8.5	
					–3.5	–0.7	4.2	6.8	5.7	–0.4	–0.9	–2.4	–0.2	–3.1	–2.0	–2.9
91. ANTARCTIC OCEAN: Adélie Land																
Port Martin[18]	66°49S	141°24E	Aug., Sept. 1950, Feb., May–Oct., 1951			7.2			–0.8	–11.8	3.2	–5.8	4.2	3.7		
Cape Denison[19]	67°00S	142°40E	June–Aug., 1912							–8.1	–1.4	–4.8				
						7.2			–0.8	–10.0	0.9	–5.6	4.2	3.7		
92. ANTARCTIC OCEAN: Macquarie Island																
Macquarie Island[19,20]	50°31S	158°58E	Aug. 1912–May 1913		–6.0	–12.1	–1.7	5.0	–4.5			–0.5	8.6	4.7	–2.3	9.2

FOOTNOTES

[1] Values taken as positive downward though given as positive upward. Confirmed by letter from J. A. Barahona Fernandes. The error seems to have arisen out of a confusion between "dessous" and "dessus"!

[2] Unpublished data furnished by Liverpool Observatory and Tidal Institute.

[3] (a) Thomson tide gauge, (b) Mier tide gauge.

[4] Changed October value from 7.778 to 6.778.

[5] Unpublished data from U. S. Coast and Geodetic Survey.

[6] Changed March value from 1.93 to 2.93.

[7] Combined La Coloma, 22°14N 83°34W, and Los Arroyos, 22°21N 84°23W.

[8] Report of the International Polar Expedition to Point Barrow, Alaska, by Lt. P. H. Ray, Washington, 1885.

[9] Omitted data for March, 1951.

[10] Three years data for August and September only; two years data for remaining months.

[11] July, August, September, 1948, February through August, 1949, February through April, 1950.

[12] Values taken as positive downward, though given as positive upward.

[13] Tidal Record 1930–49, Geophysical Survey Institute, Ministry of Construction, Japan, 1950.

[14] Values taken as positive upward, though given as positive downward.

[15] Tidal Work on Marguerite Bay, Antarctica, Ronne Antarctic Research Expedition, Office of Naval Research, 1948.
For following months data were available only for stated number of days: Feb., 17 days; Apr., 7 days; May, 13 days. Data complete for all other months.

[16] Deuxieme Expédition Antarctique Française (1908–1910, commandée par le Dr. Jean Charcot, Étude sur les Marées, by R.-E. Godfroy, Masson et C^{ie}, Paris.
For following months data were available only for stated number of days: Feb., 26 days; Aug., 6 days; Oct., 11 days. Data complete for all other months.

[17] In combining these two stations the values for the months where the data are incomplete have been multiplied by a factor proportional to the respective number of days for each station. Where the incomplete data represent a period of consecutive days at the beginning or end of a month, the months have been divided into two periods, which have been averaged separately and later combined.

[18] Nouveaux Enregistrements de Marée en Terre Adélie, by Bertrand Imbert, Extrait du Bulletin d'Information du Comité Central d'Océanographie et d'Étude des Côtes, V, 7, 1953.

[19] Australasian Antarctic Expedition, 1911–1914, Scientific Reports, Series A, Vol. II Oceanography, Part 2 Tidal Observations by A. T. Doodson, Dec. 1939.
Data available for stated number of days: June, 20 days; July, 22 days; Aug., 31 days.

[20] Analysed in separate months of 29 days each.

[21] Values may reflect other than oceanic conditions; station located upriver or at estuary head.

APPENDIX II

ATLANTIC OCEAN (ARCTIC SECTOR)

No.	Locality	Latitude	Longitude	BTs/Mo.	NB	Reference		J	F	M	A	M	J	J	A	S	O	N	D
1.	Barents Sea	70°–76°N	033°–040°E	0	62	Conseil (1904)	z_T		1.1			−1.3			−1.6			1.7	
							z_S		0.4			0.5			0.0			−0.7	
							z_α		1.2			−0.5			−1.5			0.8	
							ATLANTIC OCEAN												
2.	Norwegian Sea	65°–71°N	006°W–006°E	0	163	HYDRO	z_T		−6.8			−0.6	−0.4	1.8	3.2	2.7			
							z_S		2.0			0.3	−0.5	−0.3	−0.2	−1.4			
							z_α		−4.3			−0.4	−1.1	1.4	3.2	1.4			
3.	North Sea	55°–60°N	005°–010°E	57[1]	unk.	Dietrich (1950)	z_T	−1.0	−4.0	−4.5	−3.9	−2.7	−0.9	1.4	2.8	3.9	4.7	3.0	1.2
							z_S	0.0	−1.0	−1.3	−0.9	−0.7	−0.4	0.0	0.7	0.9	1.1	1.0	0.5
							z_α	−0.6	−2.7	−3.7	−3.7	−2.9	−1.3	0.6	2.7	4.3	3.4	2.5	1.2
4.	Bay of Biscay	40°–51°N	005°–022°W	0	unk.	Helland-Hansen (1930)	z_T	−4.7	−4.7	−4.6	−4.5	−2.0	1.1	4.3	6.1	5.6	4.5	2.6	−3.5
5.	Station "K"	45°N	016°W	0	19	COEC (1951)	z_T	−2.5	−3.0	−3.0	2.0	2.0	1.2	1.3	1.6	1.6	2.0	−0.6	−2.0
							z_S	0.8	0.3	−0.2	−2.2	−1.5	−0.5	0.2	0.5	0.6	0.8	0.5	0.5
							z_α	−1.7	−2.4	−3.2	−0.2	0.5	0.6	1.5	2.1	2.2	2.8	−0.2	−1.6
6.	Off Gibraltar	32°–37°N	010°–015°W	104[1]	—[2]	WHOI	z_T	0.3	−2.4	−3.5	−3.7	−2.6	−0.9	0.7	2.1	2.6	2.3	3.3	1.8
7.	Mediterranean	35°–40°N	015°–020°E	163[1]	—[2]	WHOI	z_T	−3.0	−4.6	−5.3	−5.4	−2.0	−0.2	3.2	3.4	2.3	5.2	5.8	0.4
8.	South of the Azores	32°–37°N	026°–031°W	87[1]	1	WHOI	z_T	1.9	−0.2	−3.2	−4.1	−4.7	−4.8	−2.8	−0.3	3.1	5.2	5.3	4.6
9.	Capetown	33°–36°S	012°–018°E	0	30	DISCOVERY (1944)	z_T	−3.1	−3.8	4.0	10.0	8.3	2.6	−15.1	−21.5	−10.6	6.8	13.0	9.3
							z_S	−1.7	3.6	0.6	−1.9	−2.5	−1.1	6.6	9.5	3.4	−4.8	−7.1	−5.9
							z_α	−5.0	−0.8	4.9	8.3	6.0	0.8	−8.3	−11.3	−7.1	2.3	6.6	3.6
10.	40,000 South	38°–42°S	001°W–003°E	0	15	DISCOVERY (1944)	z_T	1.5	2.2	2.9	2.2	0.3	−0.1	−0.1	−1.3	−2.6	−3.1	−1.9	0.0
							z_S	1.2	0.1	−1.4	−1.5	−0.1	0.5	0.2	−0.3	−0.8	−0.1	0.9	1.2
							z_α	2.7	2.4	1.6	0.8	0.2	0.3	0.1	−1.6	−3.3	−3.1	−1.1	1.1
11.	Falkland Is.	52°S	052°W	0	unk.	Deacon (1933)	z_T	1.8	3.2	4.5	4.6	3.9	1.1	−1.8	−4.2	−5.0	−4.6	−2.8	−0.4
							z_S	−0.7	0.2	0.7	1.2	1.5	1.1	0.5	0.0	−0.4	−1.1	−1.5	−1.3
							z_α	0.9	3.7	5.4	6.4	5.5	2.0	−1.3	−4.4	−5.9	−6.0	−4.6	−1.8
12.	Recife	04°–09°S	030°–035°W	12[1]	2	WHOI	z_T	1.1	2.2	3.3	2.8	0.1	−2.0	−2.4	−2.0	−1.6	−1.0	−0.6	0.0
13.	Puerto Rico	15°–20°N	063°–068°W	91[1]	3	WHOI	z_T	−2.5	−4.8	−4.5	−2.2	−0.1	0.7	1.1	2.0	3.4	4.1	2.6	0.2
14.	Gulf of Mexico	22°–27°N	082°–087°W	166[1]	4	WHOI	z_T	1.6	−2.7	−5.3	−4.7	−2.1	−0.2	1.0	1.9	2.2	2.3	3.2	2.9
15.	Florida C.	33°–35°N	070°–075°W	76[1]	1	WHOI	z_T	−5.3	−6.5	−8.8	−9.3	−5.0	0.4	4.5	8.4	10.0	8.5	3.5	0.6
16.	Bermuda	31°–34°N	062°–068°W	99[1]	132	Fuglister (1947)	z_T	−2.3	−4.9	−6.6	−6.9	−5.6	−3.8	0.3	4.5	7.6	8.9	6.7	2.2
							z_S	−0.1	−0.1	0.0	0.0	0.3	0.5	0.5	0.1	−0.3	−0.6	−0.4	0.0
							z_α	−2.6	−5.0	−6.4	−6.8	−5.3	−3.4	0.7	4.7	7.3	8.5	6.4	1.9

17. East Sargasso	30°–35°N	045°–050°W	101[1]	—[2]	WHOI	z_T	−0.8	−2.2	−3.9	−4.4	−2.7	−1.3	0.9	2.4	2.6	3.7	3.5	2.2
18. North of Bermuda	34°–37°N	062°–068°W	70[1]	73	Fuglister (1947)	z_T	−7.3	−10.6	−11.4	−10.2	−7.0	−2.0	5.0	10.9	14.0	12.0	6.4	0.3
						z_s	0.1	0.0	−0.2	−0.2	−0.1	−0.2	0.0	0.4	0.4	0.1	0.1	0.0
						z_α	−6.6	−10.1	−11.5	−10.6	−8.4	−2.3	5.2	11.6	14.8	12.2	6.5	−0.8
19. Gulf Stream	35°–37°N	070°–075°W	875[1]	—[2]	WHOI	z_T	−3.7	−5.4	−6.8	−5.5	−2.6	0.9	3.5	4.7	5.7	6.0	4.0	−0.7
20. Nova Scotia	40°–45°N	060°–065°W	506[1]	—[2]	WHOI	z_T	−0.9	−5.2	−9.7	−8.6	−5.5	−1.2	1.8	3.5	6.0	7.0	7.2	5.2
21. Newfoundland	47°–52°N	043°–048°W	146[1]	2	WHOI	z_T	−1.4	−2.7	−5.0	−4.1	−3.7	−1.8	1.0	2.8	3.8	3.7	3.1	3.2
22. Irminger Sea	60°–65°N	030°–035°W	267[1]	1	WHOI	z_T	−1.3	−2.5	−3.4	−3.3	−1.7	0.8	2.0	2.8	3.1	2.9	1.3	−0.7
						ARCTIC OCEAN												
23. Point Barrow	72°–73°N	156°–159°W	17	1	Worthington (1953)	z_T				−0.4					0.4			
						PACIFIC OCEAN												
24. Aleutian Is.	52°–53°N	179°E–180°	8	1	Pattullo (1950)	z_T	−0.4	−1.1	−1.4	−1.3	−0.8	−0.6	−0.6	0.5	1.7	1.4	1.6	0.8
25. Kodiak I.	56°30′N	152°30′W	unknown	1	Robinson (in press)	z_T	−0.8	−2.7	−3.2	−2.3	−1.7	−1.2	0.1	2.1	3.6	3.2	2.0	0.5
26. Gulf of Alaska	55°–60°N	145°–150°W	17	1	Robinson (in press)	z_T	0.8	−0.5	−1.5	−2.0	−1.9	−0.8	0.1	0.5	0.8	1.4	1.6	1.4
27. Vancouver I.	47°30′N	127°30′W	unknown	2	Robinson (in press)	z_T	−1.5	−2.5	−3.0	−2.9	−1.8	−0.2	1.6	3.1	3.8	2.4	1.1	−0.3
28. California C.[3]	36°–37°N	121°–122°W	0	1100	Skogsberg (1936)	z_T	1.2	−0.5	−1.3	−2.4	−3.6	−3.6	−1.8	−0.1	2.0	3.0	3.4	3.8
	32°–33°N	117°–118°W	12	5	SIO													
29. Ecuador	01°–06°S	080°–090°W	0	38	DISCOVERY (1949)	z_T		−0.2					0.6	1.8			−2.3	
						z_s		2.2					−1.8	−1.5			1.1	
						z_α		2.1					−1.1	0.2			−1.2	
30. Peru C.	09°–17°S	075°–085°W	0	38	DISCOVERY (1949)	z_T	−0.3	6.9				−3.7	−0.1	−2.7				
						z_s	1.4	−1.4				0.8	−0.6	−0.4				
						z_α	1.1	5.9				−2.9	−0.9	−3.1				
31. Station "Nan"	29°–31°N	139°–141°W	95	1	Robinson (1951)	z_T	−1.6	−2.4	−3.2	−3.3	−2.7	−1.5	0.8	2.8	3.6	3.0	3.8	0.4
32. Station "Papa"	48°–50°N	147°–149°W	56	2	LaFond	z_T	0.6	−0.4	−1.8	−2.5	−1.8	−1.0	0.9	1.8	2.1	1.8	0.8	0.8
33. Stn. 40150	40°30′N	150°30′W	unknown	1	Robinson (in press)	z_T	−3.0	−4.7	−5.4	−4.2	−2.6	−0.7	2.6	5.6	7.4	5.8	0.7	−1.7
34. Stn. 38158	37°–39°N	157°–159°W	21	3	Robinson (in press)	z_T	−0.8	−3.3	−3.8	−2.7	−1.2	1.3	2.6	2.5	1.9	1.9	1.3	0.9
35. Hawaii	20°–25°N	157°–160°W	56	6	Leipper (1950)	z_T	−1.6	−2.1	−2.3	−2.6	−2.0	−0.6	1.1	2.7	4.0	3.2	1.3	−0.7
36. Stn. "Quebec"	42°–44°N	166°–168°W	19	1	SIO	z_T	−4.1	−3.6	−0.8	1.8	0.9	−0.5	−0.6	1.5	3.5	2.3	0.3	−0.7
37. Stn. "Queen"	41°–43°N	172°–174°W	59	1	SIO	z_T	−2.5	−3.2	−3.2	−2.0	0.1	0.4	1.0	3.7	4.7	2.4	0.1	−1.3
38. Stn. "Victor I"	33°–35°N	172°–174°E	28	2	SIO	z_T	−2.0	−3.8	−3.5	−2.2	−0.7	1.7	2.6	2.2	2.9	2.7	1.4	−0.6
39. Stn. "Victor II"	30°–32°N	163°–165°E	48	2	SIO	z_T	−3.0	−4.7	−5.8	−6.9	−7.1	−3.6	2.3	4.4	5.7	7.9	7.4	2.9
40. Marshalls—15°N	14°–16°N	155°–175°E	unknown		Mao (1953)	z_T	Apr. through Sept.			8.4	Oct. through Mar.			−8.4				
						z_s	Apr. through Sept.			0.3	Oct. through Mar.			−0.3				
						z_α	Apr. through Sept.			8.8	Oct. through Mar.			−8.8				
41. Eniwetok	10°–12°N	161°–163°E	9	2	Robinson (1952)	z_T	0.0	−1.4	−3.4	−5.2	−4.0	−0.4	3.2	4.5	3.6	1.7	1.3	0.0

No.	Locality	Latitude	Longitude	BTs/Mo.	NB	Reference		J	F	M	A	M	J	J	A	S	O	N	D
42.	Marshalls—3°N	02°–04°N	155°–175°E	unknown		Mao (1953)	z_T	Apr. through Sept.			−3.0	Oct. through Mar.			3.0				
							z_s	Apr. through Sept.			2.8	Oct. through Mar.			−2.8				
							z_α	Apr. through Sept.			−0.4	Oct. through Mar.			0.4				
43.	Samoa	15°–19°S	170°–174°W	[illegible]	1	SIO	z_T	−1.4	0.4	1.3	1.4	1.2	1.5	0.7	−0.4	−0.8	−0.5	−1.0	−2.5
44.	New Caledonia	20°–25°S	160°–165°E	25	3	SIO	z_T	6.3	5.7	5.8	6.2	2.1	−5.7	−10.2	−5.1	−3.8	−2.5	−0.4	1.7
45.	Tasmania	42°–43°S	148°–149°E	0	13	CSIRO	z_T	−4.4	1.8	5.8	8.0	8.8	7.9	4.9	−0.5	−7.4	−10.8	−7.4	−5.6
							z_s	5.3	5.3	0.3	−3.4	−4.2	−5.7	−4.8	−3.4	−0.3	3.1	3.1	3.8
							z_α	0 9	7.0	5.0	4.2	4.0	3.3	0.0	−3.9	−7.6	−7.6	−4.3	−2.0
46.	Sydney	34°–35°S	151°–152°E	0	64	CSIRO	z_T	−17.8	−13.4	−3.9	6.7	10.1	9.5	7.8	11.4	12.8	3.5	11.3	−17.3
							z_s	8 9	9.7	8.4	4.1	−0.9	−5.5	−7.8	−8.8	−8.2	−5.6	0.0	5.6
							z_α	−8.2	−3.0	3.9	10.4	9.1	4.1	0.3	3.1	5.1	−2.2	−11.3	−11.2
47.	Truk	05°–10°N	150°–155°E	0	58	JAP-HYDRO	z_T	−4.3	6.3	8.1	3.2	8.1	5.1	2.6	1.2	−6.8	−9.2	−9.4	−6.4
							z_s	−0.2	−0.2	0.3	0.3	0.1	−0.2	0.0	0.6	0.5	−0.2	−0.6	−0.3
							z_α	−3.3	6.4	7.6	4.0	8.6	5.2	2.9	1.5	−6.4	−9.3	−10.0	−6.8
48.	Sulu Sea	07°–12°N	117°–123°E	13	7	Leipper (1947)	z_T	−2.1	−2.9	−3.0	−2.4	−1.9	0.5	0.5	0.9	3.6	5.0	2.6	0.0
49.	Mindanao Deep	09°–10°N	126°–128°E	unknown	3	Leipper (1947)	z_T	−4.6	−2.8	−2.0	−2.3	1.7	3.1	1.1	0.6	1.0	0.9	2.7	−0.1
50.	Manila	14°–16°N	118°–120°E	7	5	Leipper (1947)	z_T	−1.8	−3.1	−3.9	−5.3	−4.1	0.9	4.3	3.4	2.6	3.5	3.0	0.5
51.	Marianas	18°–20°N	145°–150°E	0	36	JAP-HYDRO	z_T	−7.1	−3.4	−2.6	0.9	−0.3	3.0	4.9	4.2	5.1	1.4	−1.7	−6.0
							z_s	−1.2	−1.9	−1.2	−1.2	−0.7	0.3	1.4	1.6	0.2	1.3	0.7	0.7
							z_α	−7.3	−5.5	−4.1	−0.4	−1.3	3.1	6.1	6.8	5.2	8.9	−1.2	−5.9
52.	Formosa	23°–24°N	122°–123°E	0	198	JAP-HYDRO	z_T	−6.2	−4.7	0.9	3.3	2.8	1.2	1.1	4.0	4.7	1.3	−3.7	−6.1
							z_s	1.3	0.3	−3.3	−3.8	−2.4	−0.8	1.6	2.7	2.2	1.3	−0.7	1.9
							z_α	−4.3	−3.8	−2.1	−0.2	0.3	0.3	2.4	6.1	6.3	2.4	−3.8	−3.7
53.	Okinawa	26°–27°N	126°–127°E	0	171	JAP-HYDRO	z_T	−1.8	−1.3	−4.3	−5.2	−2.1	3.5	8.9	3.6	2.4	−0.2	−0.8	0.0
							z_s	−4.6	−5.8	−2.0	−1.3	−0.7	0.4	1.0	3.0	4.2	4.8	3.7	−1.9
							z_α	−6.3	−7.1	−6.3	−6.4	−3.0	2.6	9.9	6.6	6.6	4.5	1.3	−1.9
54.	Stn. "Tango"	29°–30°N	135°–136°E	0	80	JAP-HYDRO	z_T	−4.1	−7.0	−8.1	−8.4	−6.5	−1.6	3.2	6.7	9.1	10.9	5.8	−0.8
							z_s	−0.7	−0.8	−0.6	−0.1	0.5	0.9	0.9	1.0	0.5	0.0	−0.5	−0.9
							z_α	−5.1	−8.5	−9.6	−9.4	−6.9	−2.5	4.6	8.8	11.1	12.5	6.2	−1.7
55.	Kuroshio[3]	unknown		0	unk.	Koenuma (1939)	z_T	−4.4	−5.5	−6.2	−6.4	−6.2	−3.2	−0.4	4.4	8.7	9.8	6.7	1.8
		34°–35°N	139°–140°E	0	118	Japanese	z_s	0.6	−0.7	−0.7	1.4	1.8	−1.5	−4.0	−2.0	1.2	2.4	1.9	1.4
		37°–38°N	142°–143°E	0	216	JAP-HYDRO	z_α	−4.4	−6 6	−7.2	−5.2	−4.6	−4.8	−3.7	2.3	10.8	12.6	8.6	2.5
56.	Korea	39°–40°N	129°–130°E	0	117	Japanese	z_T	−3.7	−4.8	−5.1	−3.6	−1.0	0.1	1.9	3.4	3.[illegible]	4.4	3.8	1.0
							z_s	0.3	−0.4	−0.5	−1.3	−1.7	−0.4	−0.3	0.5	1.4	0.7	1.1	0.6
							z_α	−3.4	−5.0	−5.1	−5.0	−3.3	−0.9	1.4	4.2	5.2	5.5	5.0	1.3
57.	Central Sea of Japan	38°–39°N	135°–136°E	0	84	Japanese	z_T	−6.8	−12.5	−10.7	−6.6	−5.0	−4.6	−1.7	7.0	13.0	13.8	9.3	4.7
							z_s	0.4	−0.3	−0.7	−0.8	−0.9	−1.0	−0.7	−0.1	0.4	0.9	1.2	1.3
							z_α	−6.9	−11.2	−10.8	−7.4	−6.4	−6.2	−3.3	6.1	13.7	15.4	11.0	5.9

58. Oyashio C.	41°–43°N	144°–146°E	0	141	JAP-HYDRO	z_T	2.8	−6.6	−9.2	−9.4	−7.3	−3.7	0.3	6.3	8.4	6.4	7.6	4.4
						z_S	5.2	4.2	3.8	6.7	2.8	2.4	−4.0	−7.3	−11.8	−7.3	0.4	6.3
						z_α	7.2	−2.5	−5.1	−2.3	−4.9	−1.7	−4.2	−1.1	−2.8	−0.9	8.1	10.2
59. Stn. "Sugar"	43°–45°N	164°–166°E	24	2	SIO	z_T	−2.8	−3.5	−3.8	−3.5	−2.2	0.0	2.2	3.8	3.2	3.0	2.7	0.2
60. Station "Sierra"	47°–49°N	161°–163°E	38	1	SIO	z_T	−1.2	−2.2	−2.4	−2.9	−2.4	−0.5	0.5	2.3	3.8	3.6	1.6	−0.2
						INDIAN OCEAN												
91. Perth	32°–33°S	113°–114°E	0	14	CSIRO	z_T	−6.1	8.5	11.1	9.7	10.7	14.4	11.7	1.6	−7.2	−13.3	−19.5	−20.3
						z_S	6.8	7.7	−1.6	−1.9	−1.7	−1.6	−1.0	−0.4	−0.6	−3.7	−3.3	1.8
						z_α	0.0	14.6	9.4	7.7	8.9	12.4	10.7	0.8	−8.3	−16.7	−22.0	−17.9
62. Sumatra	04°–09°N	090°–095°E	10	1	SIO	z_T	−0.6	−2.2	0.8	4.0	5.1	2.9	3.5	1.6	−5.3	−7.5	−4.7	2.0
63. Bay of Bengal	17°–18°N	083°–084°E	unknown		LaFond (1954)	z_T				−6.8						6.8		
						z_S				−20.6						20.6		
						z_α				−27.4						27.4		
64. Central Arabian Sea	14°–19°N	064°–069°E	9	3	SIO	z_T	−7.8	−8.7	−6.1	−2.6	1.1	3.9	4.8	4.6	3.8	4.4	4.6	−2.0
65. Oman	18°–23°N	059°–064°E	24	2	SIO	z_T	0.9	2.6	1.8	−1.5	−1.6	7.7	2.1	−4.7	−8.6	−4.5	2.8	2.8
						ANTARCTIC OCEAN												
66. Davis Sea	65°–67°S	085°–089°E	0	19	von Drygalski (1926)	z_T	−0.2	−3.8	0.0			0.8			1.3		1.3	
						z_S	−1.3	2.1	1.9			−1.1			−0.1		−1.5	
						z_α	−1.2	1.9	1.8			−1.1			0.0		−1.4	
67. Bouvet I.	52°–57°S	003°W–004E	0	36	DISCOVERY (1944)	z_T	−0.5	0.2	−0.3	1.7	−0.4	−0.5	−0.4	0.1	0.1	0.6		−0.6
						z_S	−0.9	0.6	0.4	1.9	−1.0	0.0	1.8	−0.1	0.0	−2.0		−0.2
						z_α	−1.9	0.4	−0.2	3.5	1.8	−0.9	1.0	−0.4	−0.2	−1.9		−1.1
68. South Georgia I.	52°–53°S	037°–038°W	0	unk.	Deacon (1933)	z_T	0.8	1.2	1.0	0.6	−0.0	−0.5	−0.9	−1.0	−0.9	−0.6	−0.2	0.4
						z_S	0.1	0.7	0.7	0.2	−0.2	−0.3	−0.2	−0.1	−0.2	−0.2	−0.3	−0.3
						z_α	0.5	1.0	0.9	0.4	−0.8	−0.3	−0.7	−0.6	−0.4	−0.5	0.0	0.0
69. South Shetland I.	58°–63°S	055°–065°W	0	79	DISCOVERY (1941)	z_T		−3.3	1.6	3.1							0.0	−1.4
						z_S		2.9	−1.7	7.2							−6.6	−1.6
						z_α		−1.2	−0.5	8.8							−3.3	−3.9

FOOTNOTES

[1] Temperature data include both BT's and Nansen Bottle readings.

[2] Salinity found from scatter diagram of temperature and salinity observations and average TS relations given in *The Oceans*

[3] Data from the locations given were averaged together.

Chart 1. Seasonal departures in recorded (black curves) and steric (red) sea levels for all oceans. Each block is assigned a number. Black vertical numerals refer to group numbers in Appendix I. Connected black dots show locations of the individual tide gauge stations comprising the group. Monthly means for each station are given in Appendix I. Red numerals refer to Appendix II. Connected solid red circles indicate regions from which temperature and salinity observations were taken to compute z_α; open red circles refer to regions where temperature observations only were available, and z_T was computed (Section 3.2). Horizontal scale in each block represents time in months from the beginning of January to the end of December. Vertical scale shows monthly departures from the annual mean; each tick represents 5 cm. Recorded sea level curves (black) are drawn through monthly mean without smoothing; italic numbers following colon give estimates of the standard deviation in cm (see Section 2.42). Steric levels (red) have been subjected to some smoothing. The curves were dashed whenever monthly means were lacking. Group 38 in the high north is drawn on an insert with a special projection.

Charts 1, 2, and 3 will be found in a pocket inside the back cover.

CARBOHYDRATE IN SEA WATER[1]

By

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ABSTRACT

Substances which respond to analytical tests for carbohydrate (with anthrone or N-ethyl carbazole) were found in Pacific Coast water in quantities of from 0.1–0.4 mg/L. In coastal lagoons, however, concentrations as high as 8 mg/L were observed. Normally, most of this is in a dissolved rather than suspended state.

We have little real information about the nature and amount of dissolved organic matter in the sea. Therefore, when it was reported some time ago by Collier, et al. (1950, 1953) that substances having the general chemical properties of carbohydrates had been detected in the Gulf of Mexico in amounts up to 50 mg/L, we began an investigation to find out whether the same thing occurs in or near our area of the Pacific Coast. The earlier work of Krogh (1934), which has impressed us as one of the most important and reliable contributions to this problem, indicated a fairly constant level of dissolved organic matter, at about 5 mg/L. This conclusion, however, was intended to be applicable to the open sea, and it is entirely possible that local conditions, especially near shore, vary widely from such a norm. Indeed, the recent report of Kay (1954) on the distribution of dissolved organic carbon in the shallow waters of the Kielerbucht shows this to be true, although the maximum which he found was only about twice that which Krogh found in open water. Kay's method of of analysis was a modification of Krogh's.

Following the initial report concerning the Gulf of Mexico, already mentioned, Wangersky (1952) endeavored to identify the substances concerned and reported the isolation of a compound having the general absorption spectrum of dehydro-ascorbic acid; he also reported a substance which "gives some indication of being a rhamnoside" and which was said to be present in inshore waters in concentrations up to 0.1 g/L.

REAGENTS AND METHODS

Anthrone. Dissolve one gram of anthrone reagent[2] (recrystallized from benzene and petroleum ether) in one liter of concentrated sulfuric

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[1] Contribution of the Scripps Institution of Oceanography, New Series No. 781.

[2] The reagent used was obtained from the Jasonols Chemical Corporation, 1085 Myrtle Ave., Brooklyn 6, New York.

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acid. Store in a dark glass-stoppered bottle and keep refrigerated when not in use. Allow the freshly prepared solution to stand four hours before using. It is stable for at least one week.

N-ethyl Carbazole. Dissolve one gram of recrystallized (from ethanol and water) N-ethyl carbazole in one liter of 90% sulfuric acid which has been cooled in an ice bath. Store the solution in a dark glass-stoppered bottle and keep refrigerated when not in use. Avoid exposure to sunlight and air as much as possible. The reagent is stable for at least two days.

Standard Sucrose Solution. Dissolve 500 mg of reagent-grade sucrose in one liter of doubly distilled water and dilute 10.00 ml of this to one liter for a working standard in the range from 0 to 5 mg/L. Add a few drops of saturated mercuric chloride solution as a preservative and store in a refrigerator.

Apparatus. A 70° C (±0.2) water bath is required to develop color with N-ethyl carbazole. AMINCO absorption cells, 100 mm in light path and 16 mm outside diameter, contain about 16 ml and are suitable for the sample volumes involved. Simple adaptors can be made to permit their use in a Beckman DU spectrophotometer. Glass-stoppered Pyrex bottles of 60 ml capacity serve well as reaction vessels.

Anthrone Method. Transfer 7.5 ml of filtered sea water to a 60-ml bottle and slowly add 15.0 ml of anthrone reagent with as little mixing as possible so as to form two discrete layers. Then mix thoroughly and immediately place the stoppered bottle in a pan of water which is maintained near room temperature. Between 15 and 25 minutes later, transfer the sample to a 100-mm absorption cell and read the optical density at 627 mμ. Determine standard curves daily, diluting with doubly distilled water. The range from 0 to 5 mg/L is suitable for a 100-mm cell. Determine reagent blanks with 7.5 ml of doubly distilled water.

N-ethyl Carbazole Method. Measure a 2.5-ml sample of filtered sea water and transfer it to a 60-ml bottle. Add 22.5 ml of N-ethyl carbazole and mix thoroughly. Immediately place the sample in a 70° C (±0.2) water bath and leave for exactly 30 minutes. Transfer the sample bottle from the water bath to a refrigerator for 15 to 20 minutes and then allow it to come to room temperature. Avoid exposure to light at all times. Between 30 to 60 minutes after removal from the water bath, determine the optical density at 562 mμ. Determine standard curves and reagent blanks daily with doubly distilled water.

Discussion. Consistent results with anthrone are largely dependent upon the purity of the reagent and on the careful control of temperature immediately after the reagent and sample are mixed. The purity of the anthrone is essential in maintaining constant calibration curves. If the reagent is not recrystallized, changes as great as 25% may occur in one day; with a recrystallized reagent, less than 5% change was observed in a week. The heat of dilution resulting from mixture of concentrated sulfuric acid with the aqueous sample is sufficiently reproducible to limit the error to less than 5%.

For a given sucrose concentration, the color intensity is 20% greater in sea water of 33 ‰ salinity than in distilled water. This effect is apparently due to the chloride ion. A correction factor must therefore be used when calculating results based on standard curves and reagent blanks determined with distilled water solutions.

In general, the N-ethyl carbazole method is considerably less satisfactory. The reddish-violet reaction product is destroyed easily by sunlight and oxidizing agents, with a resultant dark green coloration. Although there is no salt error with the reagent, the procedure is more laborious and exacting because of the rigid temperature requirements.

The reactions of the reagents with a large number of carbohydrates were studied in some detail. Both have about the same sensitivity with different carbohydrates (within a factor of 2), excepting xylose and arabinose, to which anthrone is much less sensitive. The two behave about equally with sucrose, the standard which was chosen. Further details of the two methods will be reported elsewhere at a later date.

EXPERIMENTAL

Unless otherwise indicated, all samples (to be described later) were filtered through a type-HA "millipore" filter having a porosity of 0.5 μ (Goldberg, et. al., 1952). It was established that passage through these filters does not introduce extraneous carbohydrate. The material in this filtrate will be called "dissolved carbohydrate" with the full realization that it may contain some colloidal forms as well as other interfering substances which may show the same color reactions.

A number of samples of surface sea water were collected from the Scripps Pier and from the kelp beds off La Jolla, California, in May and June 1952 and in August 1954; these were analyzed for dissolved carbohydrate at various times after collection. The methods with both reagents were used on several of these; the results are given in Table I in terms of sucrose concentrations. Each value represents the average of from 2 to 11 determinations made on both untreated aliquots and

TABLE I. Carbohydrates in filtered sea-water samples. Concentrations in mg/L using a sucrose standard.

	Method			Date	
Sample	Anthrone	N-Ethyl Carbazole	Location	Collected	Analyzed
A	—	0.14	Pier	6– 9–52	6–11–52
B	—	0.22	Pier	6–11–52	6–12–52
C	0.38	0.22	Pier	6–17–52	6–18–52
D	0.29	—	Pier	8– 9–54	8– 9–54
D	0.26	—	Pier	8– 9–54	8–10–54
E	0.25	—	Pier	8–10–54	8–10–54
F	0.43 (not filtered)	—	Kelp Beds	5– 1–52	5– 6–52
G	0.30	—	Kelp Beds	4–29–52	5–14–52
G	0.37	—	Kelp Beds	4–29–52	5–18–52
G	0.22	—	Kelp Beds	4–29–52	5–21–52
H	0.30	0.11	Kelp Beds	6–18–52	6–19–52
H	0.21	0.15	Kelp Beds	6–18–52	6–20–52
H	0.45	0.38	Kelp Beds	6–18–52	6–24–52
I	—	0.35	Kelp Beds	6–18–52	6–19–52
I	0.16	0.11	Kelp Beds	6–18–52	6–20–52
I	0.20	0.25	Kelp Beds	6–18–52	6–24–52
Average	0.30	0.21			
Std. Dev.	0.09	0.08			

on portions which were evaporated to concentrate the carbohydrate material. Standard deviations within these groups of multiple analyses were 0.09 and 0.08 mg/L for anthrone and N-ethyl carbazole, respectively. Subsequently the anthrone reagent, because of its greater convenience, was used for most but not all determinations.

Table II shows carbohydrate content as a function of depth for four shallow-water stations at half-mile intervals off Scripps Pier; these samples, taken two days after the peak of a heavy phytoplankton bloom, were not filtered, and the values therefore include any

TABLE II. Carbohydrate content at shallow inshore stations off Scripps Pier on Sept. 3, 1952, following a heavy phytoplankton bloom. Concentrations in mg/L in terms of a sucrose standard. Unfiltered samples.

Depth	Station			
(m)	1	2	3	4
0	0.36	0.26	0.32	0.26
3	0.31	0.26	0.29	0.29
7	0.24			
10		0.31	0.27	0.19
20		0.24	0.22	0.15

Standard deviation of duplicate analyses of each sample : 0.06.

particulate matter hydrolyzed upon addition of anthrone reagent in concentrated sulfuric acid. Duplicate analyses were made on all samples, and the standard deviation between duplicates was 0.06 mg/L.

A number of unfiltered samples, taken from various depths in the general area 1000 to 2000 miles off the coasts of Central America and Mexico were analyzed by the anthrone method; similarly, samples from 100 to 200 miles off the coast of southern California were analyzed with N-ethyl carbazole. These results, not tabulated in detail, fell within the range below 0.7 mg/L of dissolved carbohydrate, with a slight tendency to diminution with depth.

TABLE III. Carbohydrate in coastal lagoons of the San Diego area. Concentrations in mg/L in terms of a sucrose standard.

Lagoon	Carbohydrate	Chlorinity (°/oo)
San Luis Rey	3.9	12.2
Loma Alta Creek	3.4	16.0
Buena Vista (Upper)	2.9	4.0
Buena Vista (Lower)	2.2	4.7
Encinas	0.3	18.7
San Marcos	3.4	26.8
San Elijo	5.3	22.2
Del Mar	7.9	3.4
Sorrento (Upper)	1.6	19.7
Sorrento (Lower)	0.5	19.3
San Miguel	0.3–0.9	—

Determinations with the anthrone reagent were made on filtered samples from nine coastal lagoons in the vicinity of San Diego. Results are given in Table III together with chlorinity values as an indication of the influence of fresh-water drainage, sea-water flushing during the tidal cycle, and evaporation. Encinas, Sorrento, and San Miguel lagoons are open at the mouth, thus permitting various degrees of flushing during the tidal cycle; the six other lagoons are separated from the ocean by sand bars or cobble berms. In San Miguel lagoon the indicated values gradually increased from 0.3 mg/L at the mouth to 0.9 at the upper end of an arm 300 yards inland. This lagoon was sufficiently shallow to be completely drained with each low tide. In general, there was a direct correlation between the carbohydrate content and the occurrence of visible suspended organic matter in each lagoon.

When appraising the results reported here, note that the lower end of the sensitivity range of both analytical reagents was used in most cases. The reproducibility of results, as indicated by the standard deviation among multiple analyses of the same sample, is slightly less than 0.1 mg/L. Indicated concentrations in many of the samples were not more than three or four times this amount, thus making any conclusions dubious. The mere absence or presence of two or more different carbohydrate constituents or of other substances to which the reagents may be sensitive could produce the differences observed in such cases. However, it seems definitely established that, in the open sea at least, there is in our part of the Pacific Ocean no such concentration of "carbohydrate" as has been reported in the Gulf of Mexico.

On the other hand, a small amount of such material does seem to be present in our closed lagoons as a result of land drainage or other causes, but this amount is not more than one-tenth of that in the Gulf region. And, if we may assume that particulate carbohydrate material is readily hydrolyzed by strong acids, the similarity of results from filtered and unfiltered samples indicates that the relative amount of such particulate material is small.

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Reprinted from California Journal of Mines and Geology, July, 1955, vol. 51, no. 3, pp. 209-220, figs. 1-5.

MANGANESE DEPOSITS ON THE NORTHEAST PACIFIC SEA FLOOR[1]

Robert S. Dietz *

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ABSTRACT

Sea floor dredging by the H.M.S. *Challenger,* the U.S.S. *Albatross,* the U.S.S. *EPC(R) 857,* and vessels of the Scripps Institution of Oceanography shows that extensive deposits of manganese nodules are on the deep sea floor and that crusts of manganese dioxide cover many seamounts. Sea floor photography reveals that in some places these crusts are quite continuous and the nodules are closely packed. These crusts and nodules are fully oxidized and hydrated mixtures of manganese and iron plus earthy impurities. Also, relatively high concentrations of the trace elements nickel, copper, and cobalt are present.

INTRODUCTION

One of the many significant findings of the famous *Challenger* Expedition (1873-76) was the discovery of the abundance of black hydrous manganese dioxide on the sea floor. Subsequently other vessels, notably the U.S. Bureau of Fisheries, *Albatross,* also recovered large amounts of this substance in the Pacific, confirming the fact that extensive deposits are on the deep sea floor. Recent oceanographic work in the northeastern Pacific by vessels of the Scripps Institution of Oceanography and the U.S. Navy have provided additional information on submarine manganese deposits. The present paper is a summary of knowledge of manganese in the northeastern Pacific.

Acknowledgments. The writer is indebted to several of his colleagues at the Navy Electronics Laboratory and the Scripps Institution of Oceanography for useful ideas and information. Critical reading of the first draft of the paper by H. W. Menard, E. Goldberg, and M. N. Bramlette was especially helpful. D. F. Hewett of the U.S. Geological Survey made useful comments. The chemical analyses of table 1 were

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Table 1. Chemical analyses of some manganese crusts and nodules.

Sample number	Location	N. Lat.	W. Long.	Type of sample	Mn	Fe	Co	Ni	Depth
NH-47	N.E. of Hawaii	40–14	155–05	Nodule	13.2	11.6	0.25	0.40	2,790 fms.
NH-D-1†	Gilbert Seamount	52–47	150–05	Crust	23.2	9.6	0.50	0.63	800 fms.
NH-D-7	Seamount GA-3	56–10	145–15	Crust	20.9	13.4	0.40	0.37	800 fms.
667	Erben Seamount	32–56	132–30	Crust	25.6	11.4	0.90	0.40	390 fms.
26-A-3	Seamount 19171	19–25	171–00	Nodule	22.2	13.2	0.80	0.52	740 fms.

* Analyses by H. E. Peterson, U. S. Bureau of Mines, Salt Lake City, Utah.

† A more complete analysis of sample NH-D-1 shows that, in addition to the above analysis, it contains percentages as follows: 3.1 CaO, 1.9 MgO, 8.4 SiO_2, 3.0 Al_2O_3, 0.50 P_2O_5, 0.13 V_2O_5, 0.90 TiO_2, 0.20 Mo, 0.55 S, 0.06 Cu, 11.0 insol., and 25.4 loss on ignition.

Table 2. Partial analyses of some sea floor manganese.

Location	Fe	Mn	Ni	Co	Depth (in fathoms)
N.E. of Hawaii 27°20′N 150°10′E	16.47	14.30	0.20	0.20	2,790
	17.99	14.44	0.32	0.21	
	16.53	14.90	0.29	0.12	
Gilbert Seamount 52°47′N 150°05′W	15.07	18.52	0.30	0.25	800
	14.78	19.95	0.31	0.31	
	14.54	19.96	0.31	0.37	
Cape Johnson Gúyot 17°04′N 177°15′W	12.86	21.40	0.60	0.61	1,000
	12.60	22.58	0.65	0.64	
	14.71	19.11	0.48	0.38	
N.E. Pacific 40°14′N 155°05′W	12.00	13.48	0.21	0.15	2,790
	12.23	13.34	0.16	0.12	
	9.16	10.78	0.24	0.07	
Sylvania Seamount 11°57′N 164°46′E	17.20	18.58	0.37	0.08	750
	15.64	15.22	0.39	0.32	
	14.50	17.62	0.38	0.24	
GA-3 Seamount 56°10′N 145°15′W	13.03	19.38	0.58	0.23	800
	12.86	22.53	0.42	0.19	
	13.29	18.69	0.53	0.35	

Analyses made on three separate pieces of the same nodule.
All results are given in weight percent.

run by Goldberg and those of table 2 through the courtesy of J. Bruce Clemmer of the U.S. Bureau of Mines.

PHYSICAL PROPERTIES AND CHEMICAL COMPOSITION OF MANGANESE

Manganese dioxide, formed in the place where it now occurs, is widely distributed in deep sea sediments as grains, nodules, and coatings on rocks. This sea floor manganese is a dull, dirty brown to an earthy black; it soils the fingers, and is easily scratched by a knife. Small black manganese dioxide grains about 0.5 mm in diameter are an almost invariable constituent of red clay and a common constituent of organic deep-sea oozes. Nodules and slablike masses of manganese dioxide are also common on the deep sea floor. These have a bulbous, reniform, or potato-like shape and are less than a centimeter to as much as 20 cm in diameter, but generally are about 5 cm. Figure 1 shows the appearance of some manganese dioxide crusts and nodules. Upon splitting, they display thin concentric onionlike growth layers formed by the discontinuous accretion of manganese dioxide. The nodules commonly have a nucleus consisting of palagonite (yellow, amorphous, hydrated alteration product of basaltic volcanic glass), a basaltic fragment, pumice, a shark tooth, or a fish tooth. Generally associated with the nodules are red clay, pumice, palagonite, shark teeth, whales earbones, and small spheres thought to be of meteoritic origin. It is a matter of common observation that rocks exposed to sea water for a long time are covered with a film of manganese—the degree of burial of a rock projecting above the bottom is often indicated by such a film. In some localities these films have apparently grown into crusts several inches thick. Figure 2 shows an example of such a thick, nodular crust enclosing indurated red clay.

Sea floor manganese is an impure mixture comparable to wad or bog manganese. In addition to manganese peroxide, this amorphous and opaque substance is composed of limonite and traces of copper, cobalt, and nickel. Also sometimes included as impurities in some deposits are found in the deposits in which the nodules are imbedded such as detrital mineral grains, clay, hydrated silica, calcium carbonate, magnesium carbonate, and calcium phosphate. Manganese is generally more abundant than iron but not always. The amount of manganese dioxide (MnO_2) ranges from a few percent in some impure crusts to as much as 63 percent. Of a total of 40 analyses made of the *Challenger* collection, one contained more than 60 percent, five between 50 and 60 percent, one between 40 and 50 percent, nine between 33 and 40 percent, and 16 between 20 and 30 percent (Murray and Renard, 1891 p. 370).

Several partial analyses of manganese dioxide crusts and nodules obtained from the sea floor by vessels of the Scripps Institution of Oceanography are presented in tables 1 and 2. Four partial analyses and one complete analysis are given in table 1. Omitting the sample from the northeast of Hawaii which is apparently impure, the four other analyses show an average manganese content of 23 percent and an average iron content of 12 percent, or approximately a 2:1 manganese to iron ratio. For these four samples, cobalt has the surprisingly high maximum value of 0.80 percent and an average value of 0.65 percent, whereas nickel shows a maximum value of 0.63 percent and an average value of about 0.50 percent. Table 2 contains some partial analyses prepared by E. Goldberg of Scripps Institution of Oceanography which give results similar to those of table 1.

CHEMISTRY OF MANGANESE IN THE OCEAN

According to Rankama and Sahama, (1950, pp. 640-653) who discuss the geochemistry of manganese in considerable detail, MnO forms about 0.15 percent of gabbro and about 0.05 percent of granite. Next to titanium it is the most abundant trace element in rocks. Chemically manganese resembles iron in many respects. The ratio of iron to manganese in igneous rocks is surprisingly constant and is about 1:0.016.

The manganese content of sea water has the low value of about 0.001 to 0.01 mg/kg. (Sverdrup, et al., 1946, p. 176) Manganese is added to the ocean by streams, by submarine eruptions, and by decomposition of

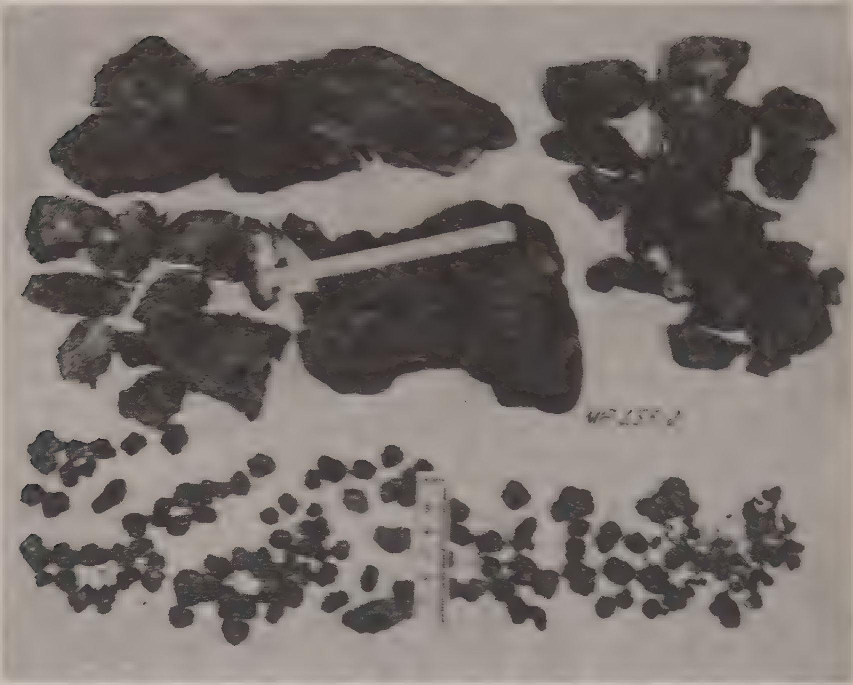

FIGURE 1. Manganese nodules and manganese-encrusted rocks recovered from a depth of [illegible] fathoms near the west end of Horizon Guyot (a guyot is a flat-topped seamount) at Lat. [illegible] N and Long. [illegible] W. In the upper right are broken manganese crusts. In the upper center and upper left are encrusted sandstones, and along the bottom of the photograph are small manganese nodules.

sea-floor rocks. A study of sea floor fathograms (Dietz, unpublished information) suggests that a large part of the Pacific sea floor is rough, and presumably rocky. Inasmuch as these rocks are probably largely manganese-rich basic eruptives it appears likely that submarine decomposition is an important source of manganese. Decomposition by carbonate- and sulfate-bearing seawater releases manganese mainly as the bicarbonate but probably also as manganese sulfate. Manganese compounds go into solution under conditions of acidic and low oxidation-reduction potential and are precipitated under conditions of high oxidation-reduction potential and alkaline conditions such as exist in the red clay. In the presence of the dissolved oxygen in the sea, the bicarbonate is quickly transformed to colloidal hydroxide which may be stabilized by organic compounds. Under proper conditions, as in the water immediately surrounding a manganese nodule or crust, manganese is precipitated as MnOOH or hydrated MnO_2. The hydrated MnO_2 rapidly loses its water of crystallization and the water found associated with deep sea nodules is adsorbed water. The botryoidal and cryptocrystalline form of the nodules shows that precipitation took place from colloidal particles rather than from ions in solution.

Unusual concentrations of certain trace elements such as cobalt and nickel are found in manganous nodules. As noted above, nickel attains concentrations as large as [illegible] percent and cobalt nearly 1 percent. These concentrations appear to depend on the manganese content and to be independent of the iron content. Both nickel and cobalt have a concentration in sea water which is far below their saturation value so that they must be selectively removed from the ocean. Goldberg (personal communication) has concluded, therefore, that these metallic positively charged ions are carried down by the negatively charged colloidal manganese hydroxide by a process of adsorption or ''scavenging.''

Manganese is an essential element to both plants and animals. Many aqueous plants are able to accumulate manganese as Mn $(OH)_4$ and manganese plays a role in the reduction of nitrates both in green plants and in green algae. Manganese can be precipitated by the removal of carbon dioxide from the bicarbonate by bacterial action or by direct oxidation. It is unknown whether or not organisms have an essential role in the formation of manganese deposits on the sea floor.

RATE OF ACCUMULATION

The rate of growth of manganese dioxide nodules has been studied by Pettersson (1943) using a radioactivity method. He concluded that the rate of growth of the two nodules examined was of the order of 1 mm per 1,000 years. But inasmuch as the rate of supply of manganese might vary over wide limits in different localities, this rate of accumulation cannot be generally applied. For example, it is possible that the manganiferous solutions forming the deposits are largely of local origin, being derived from the decomposition of volcanic rocks extruded on the sea floor in the immediate vicinity of the manganese deposits. This decomposition would proceed rapidly after the flows were first extruded, but would cease as soon as hydrothermal activity and decomposition of the upper few feet was complete. Rapid deposition of manganese compounds would take place only as long as weathering continued. Nevertheless, there is no question but that thick coatings of manganese indicate a long period of exposure to sea water. Off California, manganese dioxide films are not found on rocks of the shelf or of shallow banks shallower than about 65 fms. Such surfaces appear to have been exposed recently to surf action—presumably during the last Pleistocene lowering of sea level approximately 20,000 years ago. Subsequently there has been insufficient time for the accumulation of manganese. Rocks dredged by Menard (personal communication) from the tops of seamounts in the Gulf of Alaska showed that the basaltic country rock is commonly thickly encrusted with manganese dioxide but that erratic continental rocks presumably rafted onto the seamount by Pleistocene icebergs have, at most, a thin coating. This indicates that the accumulation of manganese is a slow process.

Erben and Fieberling Guyots (seamounts) present an interesting situation in regard to the accumulation of manganese (Carsola and Dietz, 1952). Although these banks are geographically close and appear to offer similar physical-chemical environments, a thick crust of manganese dioxide was found covering the rock dredged from Erben Guyot but only a thin coating was found at Fieberling Guyot. This is possibly because the surface of the latter guyot is younger, but it is also possible that the sampling was not representative. Fossil evidence shows that the Erben Guyot surface was cut before the middle Miocene. The age of the Fieberling surface is not known.

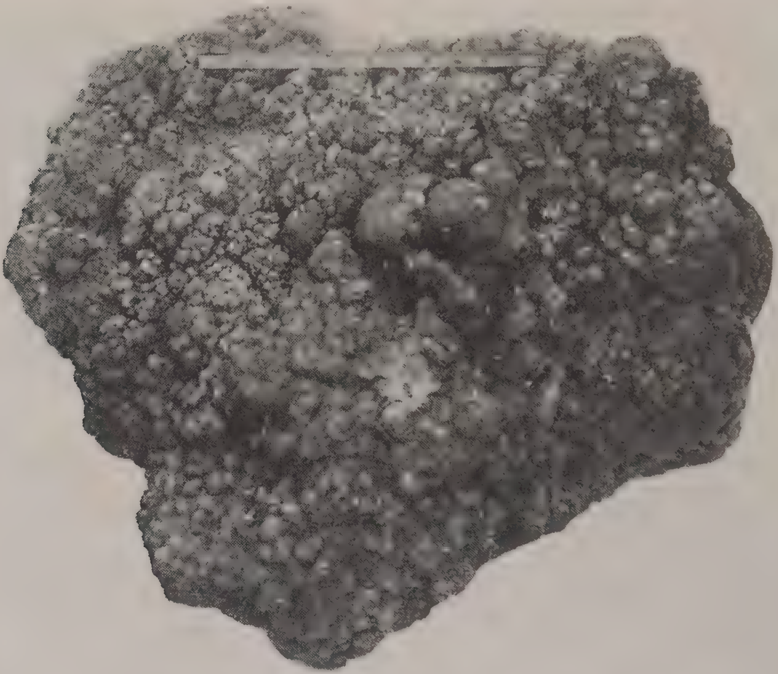

Figure 2. This large nodular mass of manganese (25 inches long, 21 inches wide, and 13 inches high) was recovered from 2790 fathoms at Northern Holiday Station 47 several hundred miles northeast of Hawaii (Lat. 40° 14′ N; Long. 155° 05′ W). This is probably the largest nodule of manganese ever recovered from the sea floor. Sectioning of the nodule showed the center to consist of an indurated layer of whitish red clay.

Thick crusts of manganese dioxide are found covering the 100,000,000-year-old mid-Cretaceous surfaces of the guyots of the Mid-Pacific Mountains (Hamilton, 1952). These crusts are of the order of several inches thick, instead of the 100 meters to be expected if a growth rate of 1 mm/1000 years is applied. Presumably either the rate of accumulation there is less than Pettersson's figure or the guyot surface has been affected by processes that would stop manganese accretion.

In summary, it appears that thick accumulations of manganese compounds probably form only on surfaces which have been exposed to oxidizing sea water for a long period of time. Environments unfavorable to the accumlation of manganese are those where sediments are being deposited, where the rocks are too recently emplaced to be weathered, or where the sea floor has been exposed to surf action of the Pleistocene lowered sea levels such as the continental shelves and the tops of shoal seamounts.

DISTRIBUTION OF MANGANESE IN THE NORTHEAST PACIFIC

Inasmuch as corers and grab samplers rarely recover rock, dredging is the only method likely to yield much information on the presence of manganese. It is not surprising then, that most information regarding manganese deposits in the Pacific has come from the *Challenger*, the *Albatross*, and vessels of the Scripps Institution, all of which have done extensive dredging.

No data are available on the percentage of manganese in bottom sediments of the Pacific, but Malloy (unpublished manuscript), by a study of the published descriptions of 1426 bottom samples taken in the Atlantic, found manganese in almost half of the red clay samples but in less than 10 percent of the globigerina ooze and blue mud samples. Inasmuch as the northeast Pacific is largely a red clay province, manganese may be expected to be common. Table 3 is adapted from Malloy's study. It shows the distribution of manganese grains, coatings, or nodules with respect to bottom type.

Occurrence in the Open Pacific. The *Challenger* reported (Murray and Renard, 1891, pp. 341-378) that ferruginous manganese nodules are among the most widely distributed objects in marine sediments, being especially characteristic of the abyssal Pacific red clays. The stations

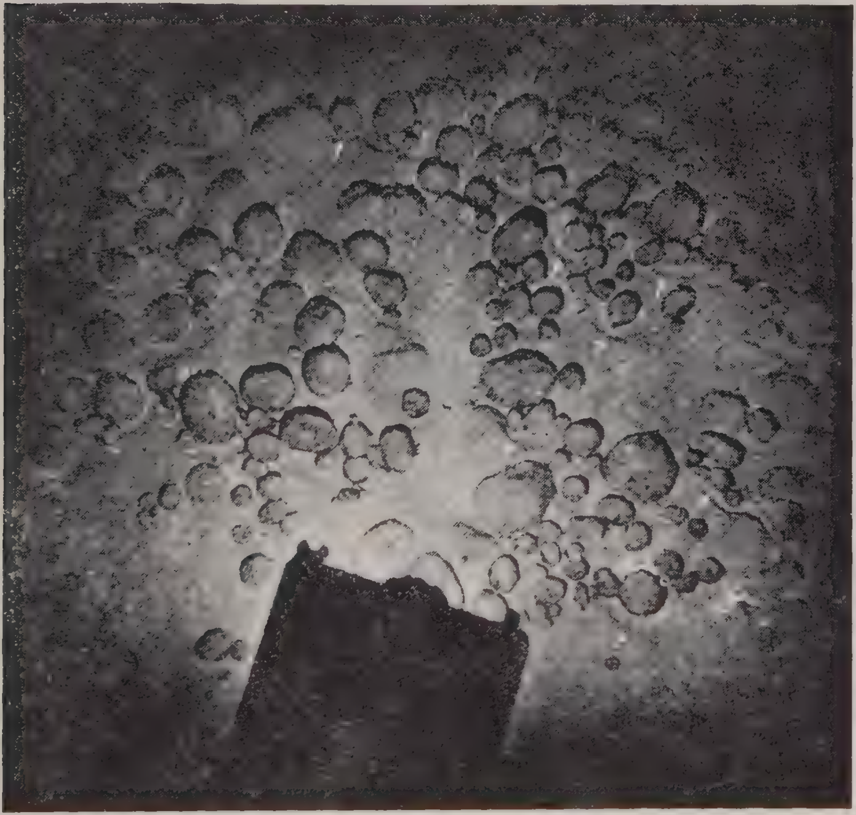

FIGURE 3. Deepest underwater photograph ever taken (3026 fathoms) showing a cluster of objects, some as much as 5 inches across on a red clay bottom. These appear to be manganese nodules, judging from their rounded and bulbous shape—note especially the potato-like form of some of them. A core sample obtained at the same spot with a corer attached to the camera stand contained abundant manganese grains. Field of view is 6 feet. Location is about 300 miles southeast of Bermuda (Lat. 30° 37′ N, Long. 59° 07′ W). Of additional interest is the evidence of current action at this great depth as indicated by (a) lack of sediment on top of the nodules; (b) scours in front of the objects, some of which are marked with an arrow; and (c) deposition of white material, presumably Globigerina ooze, in the lee of certain nodules as at the point marked "x". Some persons will find this photograph more intelligible if turned upside down so that the shadows fall toward the reader. *Photograph taken with an Ewing-Worzel camera by David Owen, Woods Hole Oceanographic Institute.*

Table 3. Distribution of manganese dioxide with respect to sediment type in the Atlantic.

Type of deposit	Number of samples	Mean depth (in fathoms)	Number of samples containing manganese dioxide	Percent of samples containing manganese dioxide
Globigerina ooze	772	1975	43	6
Blue mud	342	1268	12	4
Red clay	126	2957	54	43
Volcanic mud and sand	102	821	1	1
Pteropod ooze	40	1133	6	15
Green mud and sand	17	494	0	0
Coral mud and sand	9	1119	0	0
Diatom ooze	8	2106	0	0
Red mud	8	641	0	0
Calcareous sand	2	424	0	0

where the *Challenger* recovered large amounts of manganese in the north central and northeast Pacific are shown in figure 5. The haul at Station 252 is typical of one of their larger hauls of the nodules. Murray and Renard (1891, pp. 352-354) report:

> . . . The trawl brought up many hundreds of manganese nodules . . . .; there was no clay mixed with these nodules, having apparently been all washed away as the trawl was hauled up through the water. The largest nodules were about the size of cricket balls; they were more or less round or ellipsoidal, and when rolled on the deck they looked like a pile of dirty potatoes. . . . On the fracture of these nodules by a blow, they separated into large concentric scales.

Three stations where the *Albatross* dredged large amount of manganese are also indicated in figure 5. *Albatross* Station 2 is of special interest because of its proximity to California and because 800 pounds of nodules were dredged up at that locality (Agassiz, 1902, pp. 70-72), which is probably the largest haul from any single spot. There were also a number of slabs of rock with manganese crusts as much as 6 inches thick. At Station 13 the *Albatross* recovered another trawl full of manganese nodules ranging in diameter from 4½ to 6 inches. Off northern South America (in the region only partially covered by the lower righthand corner of figure 5) the *Albatross* recovered nodules from so many stations that Agassiz concluded that a region with an area greater than the U. S. was virtually blanketed with manganese dioxide.

Vessels of the Scripps Institution of Oceanography and the Navy Electronics Laboratory have added to our knowledge of manganese deposits by dredging on the top of seamounts. This work has demonstrated that crusts of manganese compounds several inches thick coat the tops of the seamounts. The locations of some of the most heavily encrusted seamounts are shown in figure 5. Dredge hauls from Erben Guyot and nearby Fieblering Guyot have been described by Carsola and Dietz (1952). Several manganese-encrusted guyots in the Mid-Pacific Mountains region west of the Hawaiian Islands were dredged during the Scripps-Navy Mid-Pacific Expedition, 1950. These have been described by Hamilton (1952). Dredging the Gulf of Alaska by the Scripps vessel *Horizon* revealed the presence of thick crusts of manganese dioxide on Gilbert and Miller Guyots. Returning from the Gulf of Alaska the *Horizon* recovered a large concretionary mass of manganese dioxide north of Hawaii. This 25 x 21 x 13-inch mass was

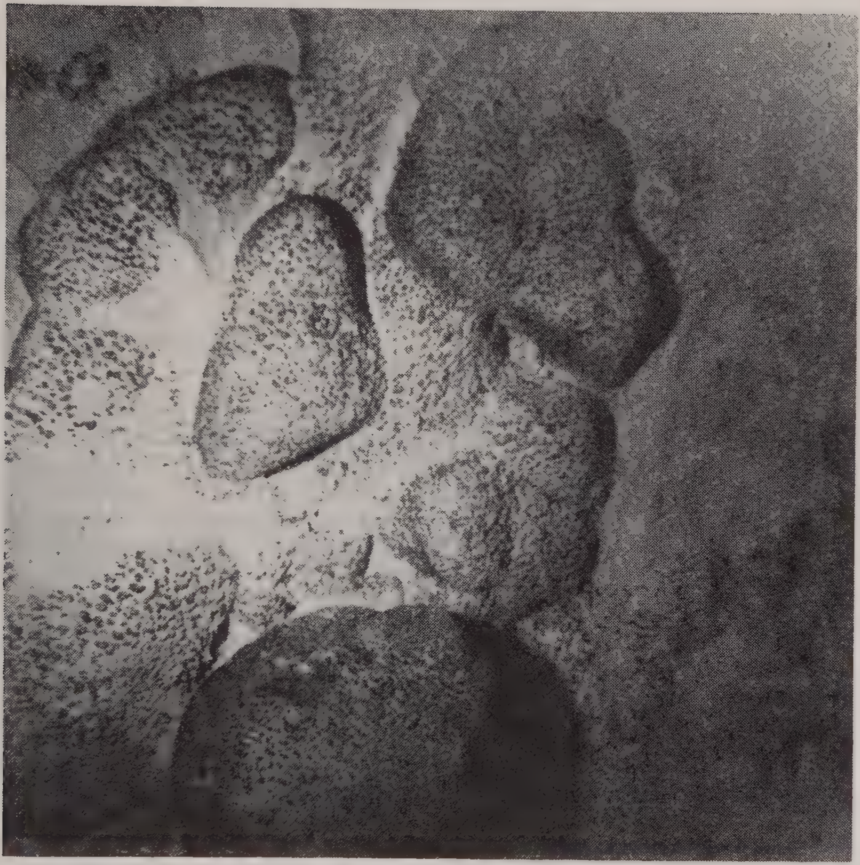

FIGURE 4. Sea floor photograph taken at a depth of 4,500 feet (750 fathoms) showing a portion of the top of Sylvania Guyot near Bikini Atoll. Rocks shown compare closely with one dredged nearby and thus are probably basalt boulders thickly encrusted with manganese. The asperities on the surface are characteristic of the manganese from this seamount. White, rippled, globigerina ooze lies between the rocks. *Photograph taken by C. J. Shipek, H. W. Menard, and the writer with a special camera developed at the Navy Electronics Laboratory. Official U. S. Navy photograph.*

snagged by excess wire rope laid on the bottom after a core had been taken. It is believed to be the largest mass of manganese dioxide ever recovered from the sea floor. Oceanographic dredges normally have an opening too small to accommodate an object of this large size.

Occurrence off Southern California. Emery and Shepard (1945, pp. 431-478) dredged rock from 132 localities in the continental borderland off southern California in 1938. They (p. 461) reported manganese dioxide cementing andesite fragments from the top of a seahill (32-16N and 117-32W; 385 fms) about 30 miles southwest of San Diego. The present writer took part in these dredgings and he recalls that a considerable quantity of manganese crusts was recovered from this locality. Also dredging from San Juan Seamount (Lat. 33° 06′ N. and Long. 120° 58′ W.) just beyond the continental slope yielded chips of manganese along with chips of basalt. A core taken near the base of this seamount recovered small fragments of manganese. It is likely

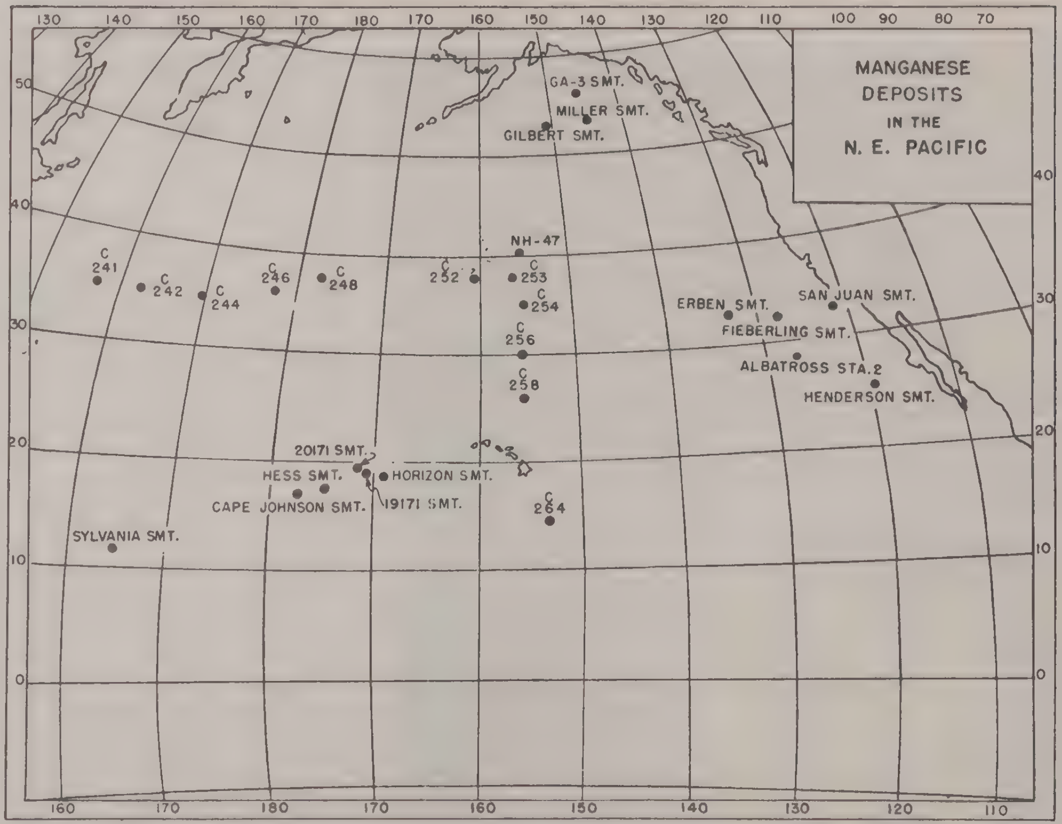
MANGANESE DEPOSITS IN THE N. E. PACIFIC
GA-3 SMT.
MILLER SMT.
GILBERT SMT.
NH-47
C 241
C 242
C 244
C 246
C 248
C 252
C 253
C 254
C 256
C 258
C 264
ERBEN SMT.
FIEBERLING SMT.
SAN JUAN SMT.
ALBATROSS STA. 2
HENDERSON SMT.
20171 SMT.
HESS SMT.
HORIZON SMT.
CAPE JOHNSON SMT.
19171 SMT.
SYLVANIA SMT.
130 140 150 160 170 180 170 160 150 140 130 120 110 100 90 80 70
160 170 180 170 160 150 140 130 120 110
50 40 30 20 10 0

FIGURE 5. Chart of the northeast Pacific showing locations where large amounts of manganese have been dredged. Those marked with a "C" are *Challenger* stations. *Albatross* Station 2 marks the position of a large dredge haul of manganese nodules obtained by the U. S. Bureau of Fisheries vessel *Albatross*. The manganese from Erben, Fieberling, and Henderson Seamounts was dredged by the Navy patrol craft *EPCE(R) 857*. The rest of the deposits are based on dredge hauls by vessels of the Scripps Institution of Oceanography.

that sampling with suitable dredges would show that this seamount is encrusted with a considerable amount of manganese dioxide.

Dietz, Emery, and Shepard (1942) and Emery and Dietz (1950), have reported on the large amounts of phosphorite recovered in connection with these dredging operations from the research vessel *E. W. Scripps.* These phosphorite nodules are typically coated with films of manganese dioxide and manganese compounds are found as partings in the interior of them. Presumably, manganese was deposited during periods of nondeposition of the phosphorite. However, the nearshore areas appear to be unfavorable environments for the deposition of large amounts of manganese.

QUANTITY OF MANGANESE ON THE SEA FLOOR AS INDICATED BY SEA FLOOR PHOTOGRAPHY

Dredging gives little information regarding the abundance of manganese on the sea floor. Although a dredge may come up filled with manganese nodules, the distance over which the dredge has been towed is always poorly known. Also, the sampling selectively and efficiency of sea floor dredges is unknown. Another complicating factor is that dredges commonly spill their loads. Thus, although a dredge may come up filled with manganese nodules, there is no proof that these objects are concentrated rather than widely dispersed over the bottom. Fortunately a visual assessment of the bottom can be obtained by photography. Although this technique is still experimental, important information on sea floor mineral deposits has already been obtained. By bottom photography Emery and Dietz (1950) demonstrated that the phosphorite deposits on the banks off southern California form continuous nodular beds covering many tens of square miles. More recently photographs have been obtained which demonstrate that manganese also is in concentrated deposits. Two such photographs are reproduced in figures 3 and 4.

Figure 3 is a sea floor photograph taken in the Atlantic near Bermuda at 3026 fathoms (18,156 feet). The objects shown are almost certainly manganese nodules. More than 200 nodules are shown. This photograph is one of the few ever taken of the deep sea floor. The fact that it shows these nodules suggests that they are common on the sea floor. Such a photograph clearly demonstrates that the nodules are present in great concentration rather than being widely dispersed over the bottom.

Figure 4 shows rocks with thick encrustations of manganese judging by the similarity of the objects in the photograph with some manganese-encrusted basalt dredged nearby. Such rugose surfaces commonly develop on manganese encrustations. The photograph was taken at a depth of 750 fathoms on the top of Sylvania Seamount near Bikini atoll.

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Reprinted from JOURNAL OF THE WASHINGTON ACADEMY OF SCIENCES
Volume 44, No. 10, October 1954
Printed in U.S.A.

ZOOLOGY.—*Geographical distribution and means of dispersal of the bathypelagic nemerteans found in the great submarine canyon at Monterey Bay, California.*

WESLEY R. COE, Scripps Institution of Oceanography.[1] (Communicated by Fenner A. Chace, Jr.)

The bathypelagic nemerteans, which are specially adapted for life in the intermediate depths of the oceans, have been found as sparse populations in all the oceans except the Arctic north of the continents. They occur most frequently at depths of 600 to 2,000 meters, and consequently their environmental conditions show relatively little variation throughout the oceans. Since many of them are believed to be transported by deep ocean currents, information concerning their known geographical distribution is of interest to both biologists and oceanographers.

In most of the bathypelagic species the body is flattened horizontally, with much gelatinous parenchyma separating the internal organs, while in some species the specific gravity is further decreased by lipoid globules in the digestive systems. Because of the density and high viscosity of the water due to low temperature and great pressure, the worms are enabled to maintain their positions with a minimum of muscular effort. Most of the species have only feeble musculatures and many of them are presumably carried passively, with slowly undulating movements, throughout the oceanic systems in the currents and eddies which they are thought to inhabit.

Relatively little is known as to the direction and velocity of these currents, although Coe (1945, 1946) has published, with the cooperation of Dr. H. U. Sverdrup, a chart of the principal known currents of the North Atlantic at the depths inhabited by the nemerteans. The available evidence indicates that these currents have an average velocity of about 1 mile in 4 days or 90 miles per year. Comparable currents in the Pacific are even less well known although their existence is fully established.

Some of the individuals recently found in the great canyon prove to be specifically identical with those of well-known species of the Atlantic, and it must have required a very long time for their ancestors to be carried from one of these oceans to the other. It should be recalled, however, that in the late Triassic era the Atlantic and Pacific had a broad connection between North and South America.

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[1] Contribution from the Scripps Institution of Oceanography, new series No.783

The collections were made by the personnel of the Hopkins Marine Station in connection with work on Office of Naval Research contract N6onr 25127, NR 163 901. All of them were obtained at the center of the outer portion of the great Monterey submarine canyon (lat. 36° 41′ 54″ N.; long. 122° 02′ 24″ W.), where the depth of water exceeds 1,000 meters. For each haul a 1-meter net was drawn for 1 hour after reaching depths of 650 to 1,160 meters and raised to the surface while still open. It is probable, however, that the nemerteans were caught at or near the lowest depths. This survey was conducted under the direction of Dr. Rolf L. Bolin and Dr. Donald P. Abbott, who have kindly provided the writer with the material which forms the basis of this report.

One or two nemerteans were obtained in each of 29 of the 141 net hauls at that locality made at intervals during two years. One or more representatives of 16 of the 29 species at present known to inhabit the Pacific Ocean were obtained. This is a surprisingly large number in consideration of the fact that only 57 species had been found previously in all the oceans of the world. Eight of the species, described elsewhere (Coe, 1954), are new to science, while the others had been recorded from distant parts of the Pacific and other oceans.

The geographical distribution, insofar as at present known, of each of the species in these collections is here indicated:

Family Protopelagonemertidae

Plotonemertes adhaerens Brinkmann—North and South Pacific and North Atlantic.

Family Planktonemertidae

Tononemertes pellucida Coe—Equatorial and North Pacific.

Family Dinonemertidae

Tubonemertes aureola Coe—North and South Pacific.
Tubonemertes (Paradinonemertes) wheeleri Coe—North Pacific and North Atlantic.
Dinonemertes mollis Coe—Equatorial and North Pacific.
Paradinonemertes macrostomum Coe—Equatorial and North Pacific.

Family Chuniellidae

Chuniella tenella Coe—North Pacific.
Chunianna opaca Coe—North Pacific.
Chunianna pacifica Coe—North Pacific.

Family Nectonemertidae

Nectonemertes mirabilis Verrill—Eastern and western Pacific, North and South Atlantic.
Nectonemertes primitiva Brinkmann—Equatorial and North Atlantic, Equatorial and North Pacific.

Family Pelagonemertidae

Cuneonemertes elongata Coe—North Pacific.
Cuneonemertes nigra Coe—North Pacific and North Atlantic.
Cuneonemertes obesa Coe—North Pacific.
Pelagonemertes joubini Coe—Equatorial and North Pacific.
Pelagonemertes rollestoni Moseley—North and South Pacific, North and South Atlantic, Indian and Antarctic.

The abundance and wide distribution of *Plotonemertes adhaerens* and *Nectonemertes mirabilis* may be correlated with their peculiar adaptions for sexual union, since the males of the former species have special glandular organs which are thought to enable them to cling to their mates, while mature males of the latter species have long, muscular tentacles supposedly for the same purpose. Internal fertilization may be assumed for all the species, although it has not been proved for any.

Pelagonemertes rollestoni appears to have a wider distribution than any of the other species, although the number of recorded specimens does not exceed 30. The translucent body with bright orange or red intestinal diverticula would make it a conspicuous object among the contents of the trawl.

Provided that the slowly moving currents presumably inhabited by many of the nemerteans are continuous throughout all the oceans, as oceanographers have concluded, and that they are continually transporting the populations of these worms not only throughout each ocean but also from one ocean to another, then it is conceivable that any of the species may eventually drift through the Monterey Bay area. A net lowered at the appropriate time might be expected to have a chance of catching an individual whose ancestors had lived or whose relatives are presently living in some far away part of the oceanic system.

The current systems presumably produce localized eddies where a population could remain and reproduce for a considerable time as is more fully discussed by Coe (1945, 1946). Eventually the members or their offspring may be swept again into the current system. It seems quite possible that the Monterey canyon contains, or did contain at the time that the collections were made, an eddy of this nature. But even there the nemertean population was far from dense considering the vast volume of water which passed through so many nets.

A similar intensive search has been made by Dr. William Beebe in the Atlantic near Bermuda, where nets 1 meter in diameter were drawn several hundred times at the appropriate depths through a circular area eight miles in diameter. There likewise, as reported by Coe (1945), a total of 14 species of bathypelagic nemerteans was found during the summers of 1929, 1930, and 1931, but it is uncertain whether these two examples with similar results indicate more or less permanent local populations or whether the captured individuals were drifting past those localities at the precise times when the nets were lowered to catch them. The hydrographic data indicate water movements of considerable magnitude at the depths at which the nemerteans were obtained.

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(Reprinted from Nature, vol. 175, p. 996, June 4, 1955)

Euphausiopsin, a New Photosensitive Pigment from the Eyes of Euphausiid Crustaceans

THE eyes of euphausiid shrimps contain large quantities of vitamin A[1]. Fisher *et al.*[1] found a particularly high concentration of the vitamin in the eyes of *Euphausia pacifica*. These observations have led to speculation that vitamin A may play a part in euphausiid vision.

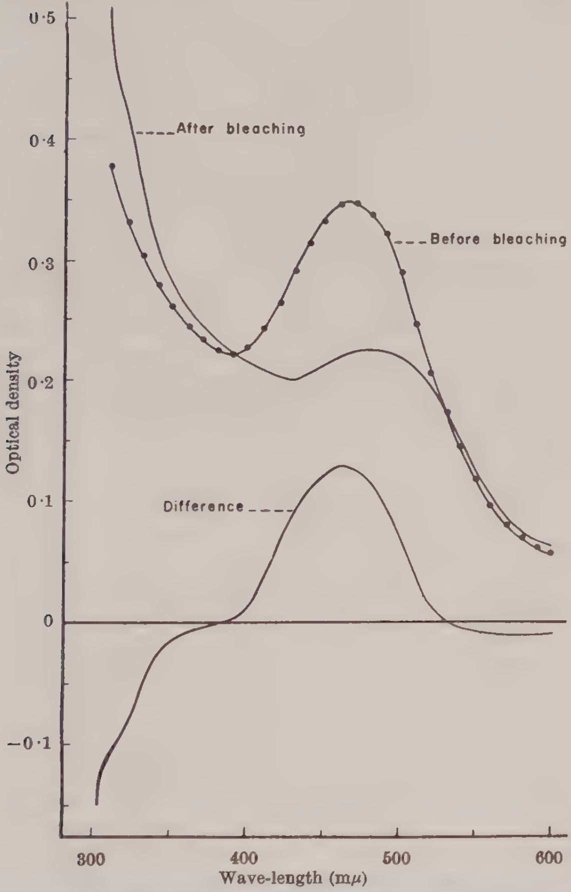

Fig. 1. Upper: Absorption spectrum of an extract of dark-adapted *Euphausia pacifica* eyes and of the same solution after 20 min. in darkness at 24° C. coincide (experimental points after 20 min. in darkness are marked ●). Absorption spectrum of the same solution after a 20-min. exposure to sunlight (marked, ——— after bleaching).

Lower: Difference spectrum obtained by subtracting optical densities after exposure to light from those before exposure to light at each wave-length

Live specimens of *E. pacifica* were dark-adapted in running sea water, and their eyes were removed in dim red light. The whole eyes were macerated with ground glass and extracted in darkness with 2 per cent aqueous digitonin (*p*H 7·2). The extracts were cleared by filtration through sintered glass.

Fig. 1 (solid line) shows a typical absorption spectrum of an aqueous extract of dark-adapted *E. pacifica* eyes. After the initial measurements were made, the solution was left in the dark at 24° C. for 20 min. The absorption spectrum was then measured again (Fig. 1, closed circles). The two spectra were indistinguishable, and it was concluded that the extract was thermally stable (subsequent experiments proved fresh extracts to be stable in darkness at 20° C. for 8–10 hr.).

The solution was then exposed to sunlight for 20 min., after which time the absorption spectrum was redetermined; and a difference spectrum was obtained by subtracting the value of optical density for the bleached solution from that for the unbleached at each wave-length.

Absorption of visible wave-lengths by aqueous solutions from dark-adapted *E. pacifica* eyes is maximal at 463–468 mμ. The position of this maximum depends upon the ratio between the concentration of a photostable pigment, probably astaxanthin, and the concentration of a hitherto undescribed light-sensitive pigment. Identification

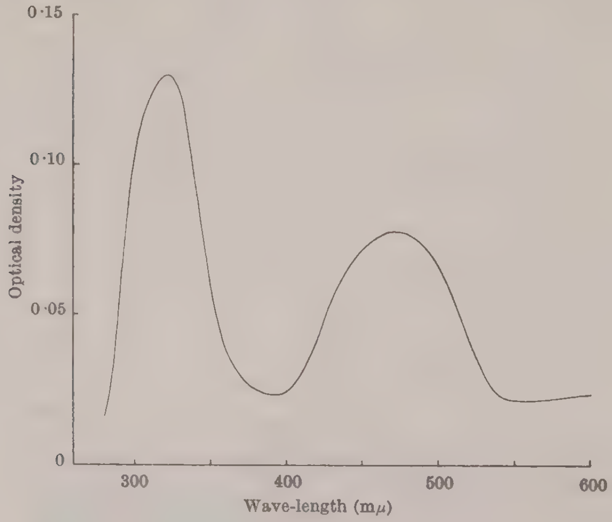

Fig. 2. Absorption spectrum of vitamin A_1 (325 mμ band) and astaxanthin (470 mμ band) in petroleum ether. This solution was obtained by extracting an aqueous extract of dark-adapted *E. pacifica* eyes with organic solvents (see text)

of the photostable contaminant as astaxanthin is supported by evidence obtained from mixed chromatograms and by the broad-band absorption in the blue-green ($\lambda_{max.}$ 470 mμ) by solutions of the contaminant in petroleum ether.

The greatest decrease in absorption caused by exposure to light occurs at 462 ± 1 mμ. Bleaching by light produces an increase in absorption in the ultra-violet. The slight hump at about 320 mμ on the direct absorption spectrum after bleaching and on the negative portion of the difference spectrum (Fig. 1) could be attributed to the release of vitamin A_1 during exposure to light.

The pigment is bleached by light of much lower intensity than that afforded by open sunlight. Difference spectra essentially identical with that shown in Fig. 1 have been obtained by placing samples of fresh extract in the light-path of the spectrophotometer for 3–4 hr. In these experiments the monochromator was set at 460 mμ, the slit width at 2 mm., and the temperature was controlled at 20° C.

Heating a sample of fresh extract to 70° C. for 20 min. in dim red light caused precipitation and a marked decrease in spectral absorption in the visible range (maximal at 468 mμ) with an increase in absorption in the ultra-violet. After exposure to heat, the solution was no longer sensitive to light.

Samples of a fresh extract were treated with equal volumes of absolute methanol, acetone and chloroform, in darkness. Each trial resulted in coagulation and loss of light-sensitivity.

These observations indicate that the euphausiid photosensitive pigment contains a protein.

Destruction of the pigment by treatment with organic reagents results in a characteristic change in the absorption spectrum. Acetone was added to a sample of the aqueous extract, and the mixture was shaken with ethyl ether. After separation, the ether fraction was dried, and the residue was taken up in petroleum ether. This solution yielded an absorption spectrum (Fig. 2) with a broad band at 470 mμ, typical of astaxanthin, and a high, narrow peak at 325 mμ, characteristic of vitamin A_1. The presence of the vitamin in bleached samples of the aqueous extract was established by the Carr–Price reaction.

Retinene (vitamin A-aldehyde) was not detected in any of the extracts.

In summary, the photosensitive pigment from the eyes of euphausiids is water-dispersable and stable in the dark at 20° C. for periods up to 10 hr. It is decomposed in darkness, and its photosensitivity is lost by heating to 70° C. or by treatment with methanol, acetone or chloroform. Decomposition of the pigment, whether by light or by treatment with organic reagents, results in a loss of colour and an increased absorption in the ultra-violet. Inasmuch as every extract so far examined has been contaminated by astaxanthin, the new pigment is probably better characterized by its difference spectrum ($\lambda_{max.}$ 462 ± 1 mμ) than by any direct absorption data at present available.

The new photolabile pigment, described here from *Euphausia pacifica*, has been extracted from the eyes of two other euphausiid species. It is proposed that the pigment be called 'euphausiopsin', after the genus from which it was first extracted.

These studies are being continued under contract between the Office of Naval Research and the Scripps Institution. I am particularly grateful to the American Philosophical Society for providing, through a grant from the Penrose Fund, the Beckman Model *DU* spectrophotometer used in the work.

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Jan. 15.

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Contributions from the Scripps Institution of Oceanography, New Series, No. 784.

Printed in Great Britain by Fisher, Knight & Co., Ltd., St. Albans.

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EUPHAUSIACEA OF THE BENGUELA CURRENT

FIRST SURVEY, R.R.S. 'WILLIAM SCORESBY', MARCH 1950

By Brian P. Boden

(Text-figs. 1–24)

ACKNOWLEDGEMENTS

THIS report was started while I was oceanographer on the staff of the Bermuda Biological Station for Research Inc. My thanks go to the succession of directors the station had during this short period for encouraging me to continue with the work at the expense of station duties.

Dr T. John Hart, National Institute of Oceanography, performed the onerous task of preliminary plankton sorting with his usual skill and patience and sent the euphausiids to me in Bermuda.

I am particularly indebted to several of the staff of the Scripps Institution of Oceanography for their critical reading of the manuscript and their numerous suggestions.

INTRODUCTION

The material upon which this report is based is drawn from the collections made by R.R.S. 'William Scoresby' during her eighth commission and her first survey of the Benguela Current off the coast of South-West Africa.

The stations occupied during this cruise are shown in Fig. 1. The collections were made in March 1950. The hauls were vertical and made with an N 70 closing-net of plankton silk of 70 meshes to the inch and with a mouth diameter of 70 cm.

Fourteen species were represented at these stations; their occurrence is given on pp. 340–45. An overall picture of distribution based on the results of a single cruise may very well be misleading, and therefore the counts are presented simply in tabular form and efforts at interpretation are postponed until the results of the second survey are available. Full station data may be obtained from the *Discovery Reports*, *Station List*, vol. XXVI. Descriptions of the South African species as adults are to be found in Boden (1954).

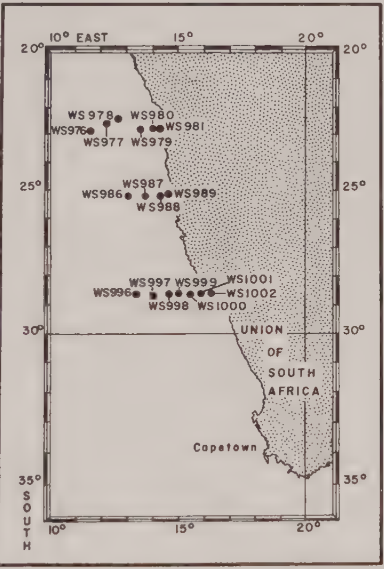

Fig. 1. Plan of stations at which euphausiids were taken during the survey of the Benguela Current by R.R.S. 'William Scoresby', March 1950.

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DISTRIBUTION OF THE EUPHAUSIACEA IN THE BENGUELA CURRENT

Thysanopoda microphthalma G. O. Sars

Thysanopoda microphthalma G. O. Sars, 1885, p. 106; *T. distinguenda* Hansen, 1905*a*, p. 17.

One adult female was taken from between 500 m. and 250 m. at station WS 977. Illig (1930) has previously reported the species from the coast of South-West Africa.

Nyctiphanes capensis Hansen

Nyctiphanes capensis Hansen, 1911, p. 19; *N. australis* Stebbing, 1905, p. 113 (*nec* Sars, 1885); *N. australis* Stebbing, 1910, p. 299; *N. africana* Zimmer, 1912, p. 3.

Table 1. *Occurrence of* Nyctiphanes capensis

Station no.	Depth (m.)	Adult males	Adult females	Larvae
WS 979	50–0	6	12	4071
	100–50	4	5	1111
WS 980	50–0	—	2	58
	100–50	1	3	173
WS 981	50–0	—	—	5
WS 988	50–0	—	—	267
	100–50	—	1	452
WS 989	50–0	—	—	454
WS 997	50–0	—	—	—
	100–50	—	—	—
	250–100	—	—	—
	500–250	—	—	—
	750–500	—	—	—
	1000–750	—	—	1
WS 998	50–0	—	—	157
	100–50	—	—	24
	175–100	—	—	7
WS 999	50–0	—	3	952
	100–50	—	—	19
	150–100	—	—	5
WS 1000	50–0	3	13	62
	100–50	—	2	10
	150–100	—	—	52
WS 1001	50–0	9	22	651
	100–50	—	11	17
WS 1002	50–0	—	1	1

The stations at which *N. capensis* was taken are shelf stations. Like other members of the genus, the species is characteristically an inhabitant of shallow, coastal waters. Good collections have been made previously in the Sturrock Dock in Capetown (Boden, 1954).

N. africana Zimmer (1912) is included here as a synonym. Zimmer's rather vague descriptions and drawings of two specimens taken from the stomach contents of the Cape snoek, *Thyrsites atun*, almost certainly refer to *Nyctiphanes capensis* and the fish were taken well within the distribution range of *N. capensis*.

Euphausia lucens Hansen

Euphausia splendens Dana *sens* G. O. Sars, 1885, p. 80; *E. lucens* Hansen, 1905*b*, p. 9; *E. uncinata* Colosi, 1917, p. 186.

Table 2. *Occurrence of* Euphausia lucens

Station no.	Depth (m.)	Adult males	Adult females	Larvae
WS 976	50–0	—	—	—
	100–50	—	—	—
	250–100	—	—	—
	500–250	—	4	5
	750–500	—	5	4
	1000–750	—	—	—
WS 977	50–0	—	1	—
	100–50	—	—	—
	250–100	—	—	—
	500–250	—	—	—
	750–500	—	—	—
	1000–750	—	—	—
WS 978	50–0	—	—	1
	100–50	—	—	—
	250–100	—	—	—
	500–250	—	1	—
	750–500	—	—	—
WS 979	50–0	—	—	14
	100–50	—	—	—
WS 986	50–0	—	—	15
	100–50	—	—	—
	250–100	2	6	1
	500–250	—	2	1
	750–500	—	—	1
	1000–750	—	—	3
WS 996	50–0	—	—	65
	100–50	—	1	6
	250–100	—	—	37
	500–250	—	—	21
	750–500	—	—	5
	1000–750	—	—	8
WS 997	50–0	—	3	14
	100–50	—	—	16
	250–100	—	1	2
	500–250	—	—	—
	750–500	—	—	1
	1000–750	—	—	10
WS 1000	50–0	36	237	—
	100–50	—	5	—
	150–100	—	—	—
WS 1001	50–0	2	18	3
	100–50	—	14	3
WS 1002	50–0	—	6	37

E. lucens is an oceanic species which flourishes in the Pan-Antarctic (Rustadt, 1930) waters. It is probable that in the waters of the Benguela Current it is approaching the limit of its range (John, 1936; Boden, 1954).

Euphausia tenera Hansen

Euphausia gracilis G. O. Sars, 1885, p. 89 (*nec E. gracilis* Dana, 1852, p. 644); *E. tenera* Hansen, 1905*b*, p. 9.

Table 3. *Occurrence of* Euphausia tenera

Station no.	Depth (m.)	Adult males	Adult females	Larvae
WS 996	50–0	—	—	5
	100–50	—	2	2
	250–100	—	—	13
	500–250	—	—	6
	750–500	—	—	1
	1000–750	—	—	6

This tropical to subtropical species occurred at only one station. Since this station is a southern one, it is probable that many of the unidentified pre-furcilia larvae encountered at other stations are really *E. tenera*.

Euphausia recurva Hansen

Euphausia recurva Hansen, 1905*b*, p. 13.

Table 4. *Occurrence of* Euphausia recurva

Station no.	Depth (m.)	Adult males	Adult females	Larvae
WS 976	50–0	—	—	—
	100–50	1	—	—
	250–100	1	2	—
	500–250	6	4	4
	750–500	7	7	—
	1000–750	—	—	—
WS 977	50–0	4	5	—
	100–50	1	—	—
	250–100	—	—	—
	500–250	—	—	—
	750–500	—	—	—
	1000–750	—	—	—
WS 996	50–0	—	—	—
	100–50	1	—	—
	250–100	1	2	—
	500–250	7	9	—
	750–500	—	—	—
	1000–750	—	—	—
WS 997	50–0	7	13	—
	100–50	2	2	—
	250–100	3	2	—
	500–250	—	—	—
	750–500	—	—	—
	1000–750	—	—	—

Evidence of diurnal vertical migration may be discerned in these data. At the day stations WS 976 and WS 996 the animals are absent from the surface layers while at the night stations WS 977 and WS 997 they are concentrated in the upper layers and absent from the lower layers.

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Euphausia hanseni Zimmer

Euphausia hanseni Zimmer, 1915, p. 180.

Four adult females of this species were taken, one from station WS 978 and three from station WS 987. All were taken between 250 m. and 100 m.

Euphausia similis var. armata Hansen

Euphausia similis var. *armata* Hansen, 1911, p. 24; *E. similis* var. *lobata* Zimmer, 1914, p. 425.

This species occurred at station WS 997. One adult male was taken between 100 m. and 50 m. and one female between 1000 m. and 750 m.

Nematoscelis megalops G. O. Sars

Nematoscelis megalops G. O. Sars, 1885, p. 127.

Table 5. *Occurrence of* Nematoscelis megalops

Station no.	Depth (m.)	Adult males	Adult females	Larvae
WS 976	50–0	—	—	10
	100–50	—	—	2
	250–100	—	—	2
	500–250	—	—	—
	750–500	—	1	4
	1000–750	—	—	—
WS 977	50–0	1	4	108
	100–50	—	—	—
	250–100	2	2	—
	500–250	—	—	7
	750–500	—	—	—
	1000–750	—	—	—
WS 978	50–0	—	—	—
	100–50	—	—	—
	250–100	—	—	37
	500–250	—	—	350
	500–350	—	—	44
	750–500	—	—	—
WS 986	50–0	—	—	37
	100–50	—	—	37
	250–100	—	—	135
	500–250	—	—	23
	750–500	—	—	—
	1000–750	—	—	2
WS 997	50–0	—	—	1
	100–50	—	—	—
	250–100	—	—	9
	500–250	—	—	—
	750–500	—	—	—
	1000–750	—	—	2

Interesting indications of diurnal vertical migration are evident in these data. Station WS 977 is a night station (21.03–03.45 hr.) and the larvae are concentrated in the upper 50 m. At station WS 978 (10.00–13.04 hr.) a premature closing of the net at 350 m. and subsequent repetition of the 500–250-m. haul reveals a concentration of larvae between 250 m. and 350 m. This, in conjunction with the layering between 250 m. and 100 m. at station WS 986 (08.05–14.07 hr.), indicates that the animals concentrate around 250 m. in the daytime. Evidence of the vertical migration of a very closely allied species, *N. difficilis*, and its possible relation to sonic scattering layers in the Pacific has been presented previously (Boden, 1950*a*).

Thysanoëssa gregaria G. O. Sars

Thysanoëssa gregaria G. O. Sars, 1883, p. 26.

Table 6. *Occurrence of* Thysanoëssa gregaria

Station no.	Depth (m.)	Adult males	Adult females	Larvae
WS 976	50–0	—	—	4
	100–50	—	—	—
	250–100	—	—	—
	500–250	—	—	—
	750–500	—	—	1
	1000–750	—	—	—
WS 996	50–0	—	—	3
	100–50	—	—	—
	250–100	—	—	—
	500–250	—	—	—
	750–500	—	—	—
	1000–750	1	—	—
WS 997	50–0	—	—	1
	100–50	—	—	2
	250–100	1	—	2
	500–250	—	—	—
	750–500	—	—	—
	1000–750	—	—	—

This species is usually quite common in this area (Boden, 1954). Its worldwide distribution is of an antitropical nature (Hubbs, 1950, 1952), although Tattersall (1926) claims that it is common in the deeper waters in the tropical oceanic area. This leads to an attractive speculation that the apparent tropical discontinuity of distribution may be associated with a submergence along temperate isotherms. Actually Tattersall's and Moore's (1952) records are not below 28° N. Brinton (Scripps Inst. of Oceanography—personal communication) finds that the species actually does seek deeper waters toward the tropical limits of its range. The limited number of deep hauls which he has made in the equatorial regions of the Pacific, however, have not yielded any specimens of *T. gregaria* and he is of the opinion that it is a true antitropical species.

Nematobrachion boöpis Calman

Nematodactylus boöpis Calman, 1896, p. 17; *Nematobrachion boöpis* Calman, 1905, p. 153.

Two adult females were captured between 750 m. and 500 m. at station WS 976.

Stylocheiron maximum Hansen

Stylocheiron maximum Hansen, 1908*a*, p. 92.

Two larvae of this species were taken, one at the 250–100-m. level at station WS 976 and the other in the upper 50 m. at station WS 986. At station WS 997 an adult female was taken between 100 m. and 50 m. and another between 500 m. and 250 m.

Stylocheiron elongatum G. O. Sars

Stylocheiron elongatum G. O. Sars, 1883, p. 32.

Eleven larvae were encountered between 1000 m. and 500 m. at station WS 976. One was taken in the upper 50 m. at station WS 997.

Stylocheiron longicorne G. O. Sars

Stylocheiron longicorne G. O. Sars, 1883, p. 32; *S. mastigophorum* (*partim*) Chun, 1887, p 30.

One larva was taken between 500 m. and 250 m. at station WS 997.

Stylocheiron affine Hansen

Stylocheiron affine Hansen, 1910, p. 118.

Five larvae were taken in the upper 250 m. at station WS 976.

A small number of unidentifiable larvae occurred at stations WS 976, 977, 978, 988, 997, 998, 999 and eggs were present in the upper layers at stations WS 976, 977, 978, 986, 996, 997, 998 and 999.

REMARKS

Physical oceanographic conditions in the Benguela Current (Currie, 1953) are somewhat similar to those found in the California Current, and a very close similarity in phytoplankton populations and successions in the two currents has been stressed by Hart (1953).

In general, the distribution of comparable species of euphausiids substantiates this similarity in the two regions. *Nyctiphanes capensis* occupies the same inshore niche in South African waters that *N. simplex* does in Californian waters. *Euphausia lucens*, reaching the northern limit of its range in the Benguela, may be compared with *E. pacifica*, which reaches its southern limit in the California Current. The distribution of *Nyctiphanes megalops* in this survey is very similar to that of *N. difficilis* in California, and that of *Euphausia recurva* and *Thysanoëssa gregaria* is the same in both regions.

Curiously enough, species with comparable distributions in the two currents show remarkable morphological similarities. The appearance of *Nyctiphanes capensis* closely resembles that of *N. simplex*. This is true of all four species of *Nyctiphanes*. These species all occur in areas of upwelling where conditions are roughly the same.

Euphausia lucens and *E. pacifica* are undoubtedly the most closely morphologically allied species in this large genus. Even the copulatory organs of the males show many points of similarity.

Nematoscelis difficilis and *N. megalops* are so closely similar that the females are inseparable. On these grounds Einarsson (1942) cancelled *N. difficilis*. The males are separable on small but consistent differences in the copulatory organs, however, and the species has, therefore, been revived (Boden, 1954).

The distribution of euphausiids in the Pacific is now fairly well understood (Brinton, unpublished) and it may become possible to draw further analogies when the results of the second survey of the Benguela Current have been evaluated.

DEVELOPMENTAL PHASES

It was possible to glean some information on the developmental phases of four of the species encountered. This is presented below.

Nyctiphanes capensis Hansen

Egg. Size range 0·34–0·38 mm. in formalin.

The eggs are carried in two pear-shaped sacs attached by their anterior broad sides to the endopodites of the sixth and seventh cormopods, and by their narrow posterior ends to the exopodites of the eighth cormopods (precisely as in *N. simplex*).

Only one female with intact egg-sacs was found in the collection (Fig. 2). There were fourteen eggs in one sac and sixteen in the other. The perivitelline space of the eggs is small (Fig. 3*a*).

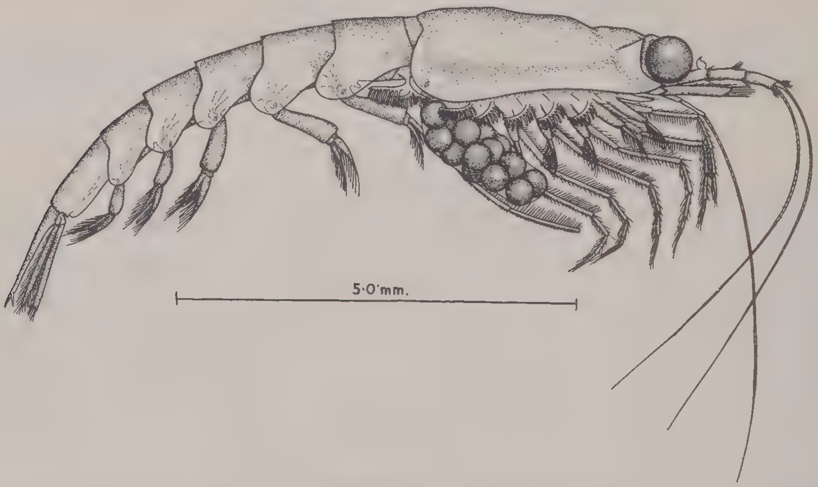

Fig. 2. *Nyctiphanes capensis.* Ovigerous female.

Nauplius. The nauplius stage (Fig. 3*b*, *c*) is passed within the egg-sac. The specimens shown in the figure were removed from the unruptured egg-sac of the female.

The length of the two specimens examined was 0·42 mm. each.

The larva is simple and egg-shaped. It has two small processes at the posterior end, each flanked by one smaller process.

The first antenna is uniramous with three terminal setae. The second antenna is biramous, the rami with four and five terminal setae. The mandible is bud-like and naked.

Pseudometanauplius. Only one specimen of this stage was found (Fig. 3*d*, *e*). It was removed from the ruptured egg-sac of a female. It is probable that the rest had already hatched out.

Length of specimen 0·48 mm. The carapace is oval in dorsal view. The first antenna is unchanged. The second antenna is the same as in the nauplius stage. A median eye has appeared. The anterior lip and buds of three metanaupliar limbs have appeared. There is now a short tail with one pair of postero-lateral and two pairs of terminal spines. The carapace, mandibles, anterior lip, limb-buds and tail are covered by a thin skin.

Metanauplius. No specimens in this stage were encountered. The metanaupliar stage is very transitory and the larva begins to eat only in the next stage. It is probably almost identical with the metanauplii of other species of this genus (cf. Lebour, 1925; Boden, 1951).

First calyptopis. Description based on examination of six specimens (Fig. 4*a–c*). Length range 0·98–1·10 mm.; average length 1·03 mm. Carapace length 0.60–0·63 mm.; average length 0·62 mm.

The carapace is a long, high, narrow dome covering the entire anterior part of the body, and it has no projections of any sort along its inferior margin.

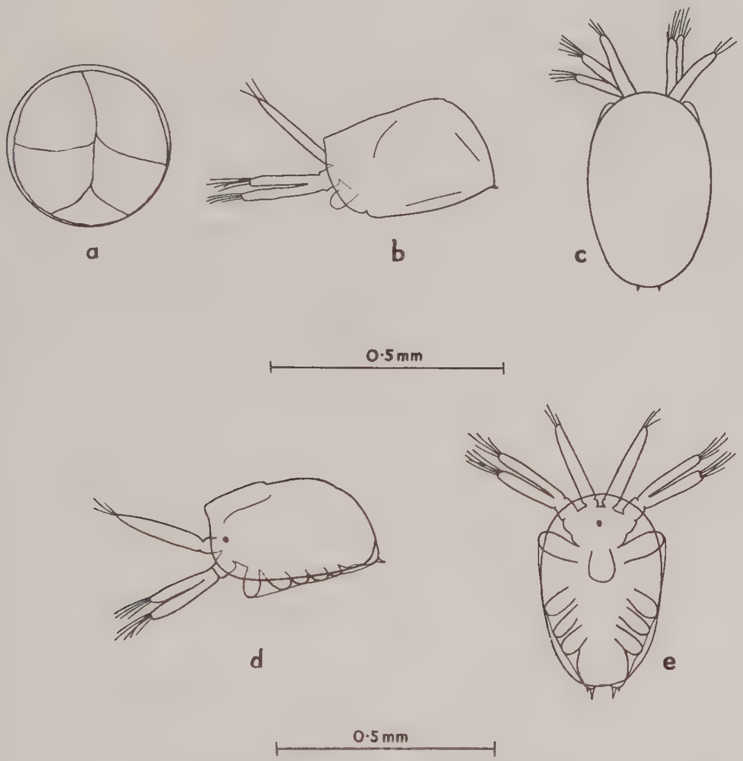

Fig. 3. *Nyctiphanes capensis.* *a*, egg; *b*, nauplius, lateral view; *c*, nauplius, dorsal view; *d*, pseudometanauplius, lateral view; *e*, pseudometanauplius, ventral view.

The single median eye is visible with the ocular plates on either side of it bearing the rudimentary ocular luminous organ.

The first antennae project forward and downward and are to all intents uniramous. The rudiments of the inner ramus can be seen, however, bearing three setae. The outer ramus carries five terminal setae. The setae are naked.

The second antennae project outward and downward and are carried on a peduncle having two segments. The anterior and longer ramus of the antennae is unsegmented and is armed terminally with four strong setose spines, and laterally with two spines. The second ramus is segmented distally and carries six terminal setose spines.

The mandible is naked and provided with strong biting jaws.

The first and second maxillae and first thoracic limb are present and very strongly resemble the same appendages in *N. australis* as figured by Sars (1885) and in *N. couchii* as figured by Lebour (1924). They are directed forward, are setose, and are used in feeding. The larva first begins eating in this stage. The thoracic segments without limbs are distinct as narrow encircling wrinkles in the integument.

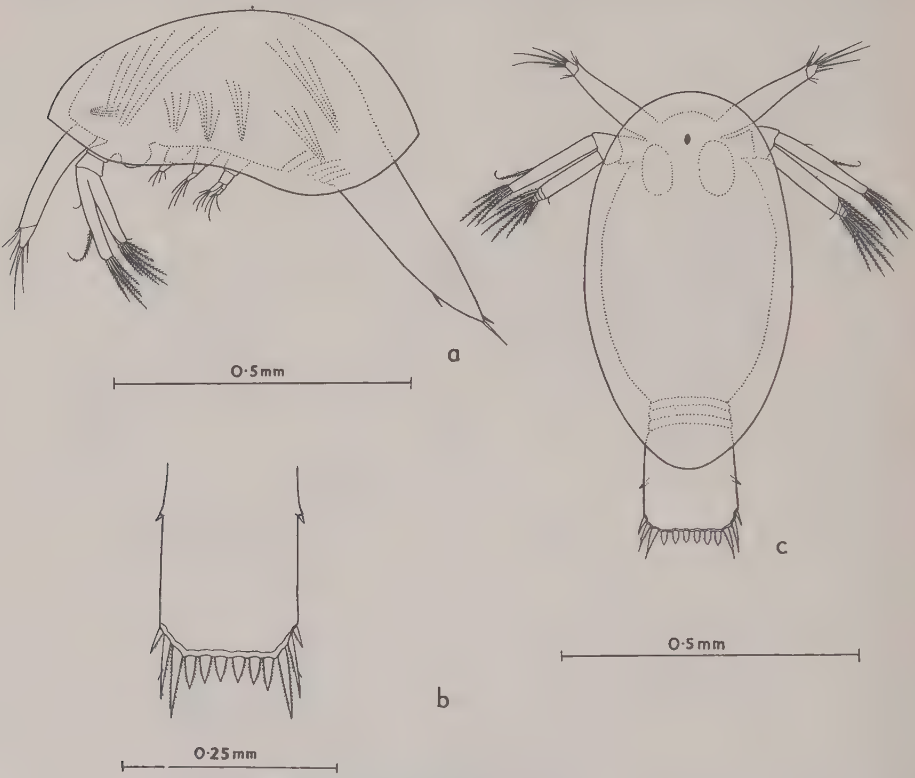

Fig. 4. *Nyctiphanes capensis*. *a*, first calyptopis, lateral view; *b*, telson of same; *c*, first calyptopis, dorsal view.

The abdomen is smooth and unsegmented. The telson has six, serrate, terminal spines decreasing in size from the outer to the inner, three pairs of serrate, postero-lateral spines increasing in size from the outer to the inner, and one pair of small ventro-lateral spines.

Second calyptopis. Six specimens examined (Fig. 5*a–c*). Length range 1·40–1·52 mm.; average length 1·46 mm. Carapace length ±0·85 mm.

The carapace is a little longer than half the total length, and is smooth along the inferior margin (cf. *N. australis*, smooth; *N. simplex*, smooth; and *N. couchii*, denticles).

The median eye is lost and the compound eyes are now well defined but not pigmented. The ocular luminous organ is visible.

There are three segments to the peduncle of the first antenna, which is biramous, the outer ramus carrying four terminal spines and the inner, three.

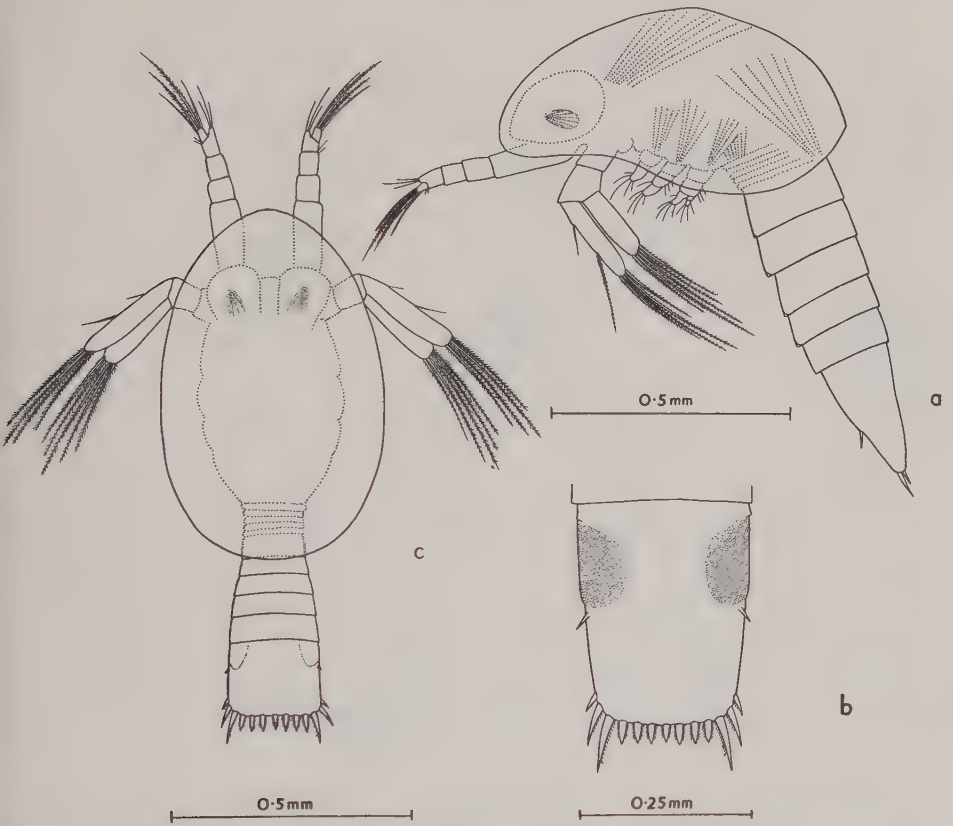

Fig. 5. *Nyctiphanes capensis*. *a*, second calyptopis, lateral view; *b*, telson of same; *c*, second calyptopis, dorsal view.

The remaining thoracic appendages are larger than in the preceding stage but are otherwise unchanged. Occasionally the rudiments of the second thoracic limb may be discerned as a small naked process. The segmentation of the thorax is clearly visible.

The abdomen now has five segments and a telson. The developing uropods can be seen within the integument of the telson. The telson retains the three pairs of postero-lateral and one pair of ventro-lateral spines of the previous stage, but now has seven terminal, serrated spines.

Third calyptopis. Six specimens examined (Fig. 6*a–c*). Length range 1·79–2·22 mm.; average length 1·90 mm. Carapace length ±0·97 mm.

The carapace is a little longer than half the total length of the larva. At this stage a small but distinct tooth appears on the inferior margin of the carapace toward its posterior end. The carapace covers the compound eyes which are now globular and distinctly pigmented.

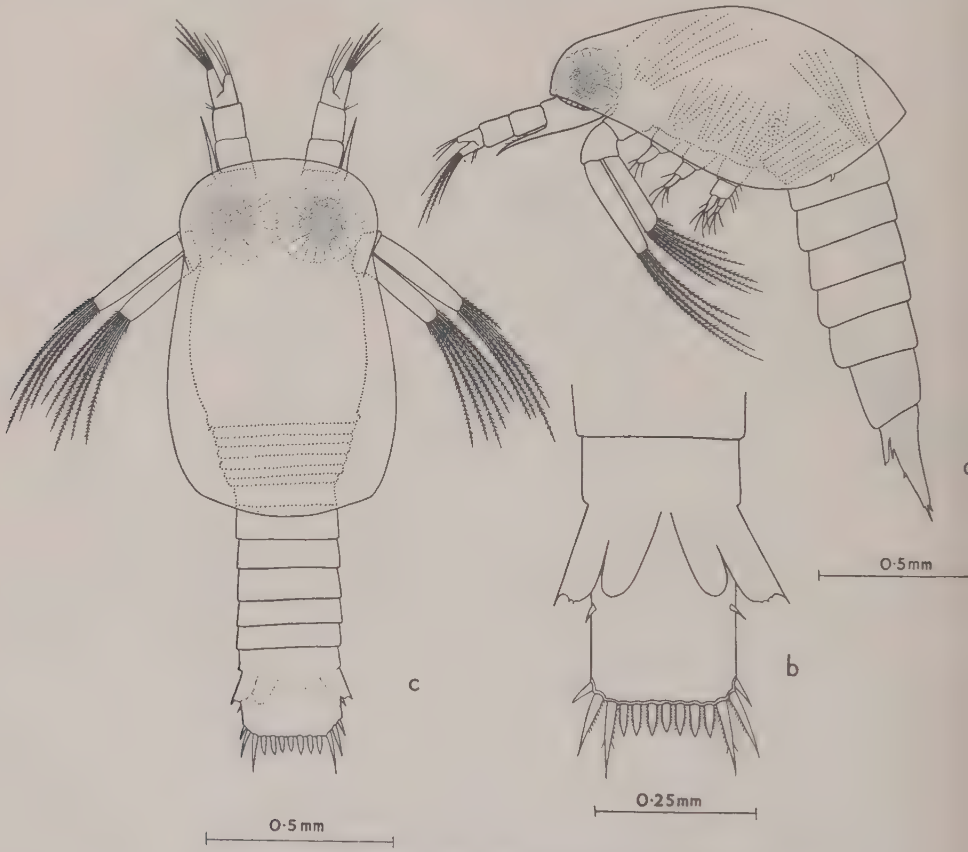

Fig. 6. *Nyctiphanes capensis.* *a*, third calyptopis, lateral view; *b*, telson of same; *c*, third calyptopis, dorsal view.

The outer, distal margin of the basal segment of the first antennal peduncle is produced as a strong, toothed spine which reaches to about the distal end of the third and last segment of the peduncle. The two rami of the first antennae remain unaltered.

The second antennae and the other thoracic appendages are much the same as in the preceding stage.

The abdomen now has six segments and a telson. There are no abdominal appendages. The two rami of the lateral uropods are now visible, the outer ramus being somewhat longer than the inner and having its outer margin produced as a strong spine. The remaining armature of the telson is unchanged.

Dominance in the furcilia stages

For reasons which have been adequately discussed before (Fraser, 1936; John, 1936; Einarsson, 1945; Boden, 1950*b*, 1951) the term 'cyrtopia' for the later larval stages has been discarded, and these stages are now included in the furcilia series. Thus the furcilia stages in this report include all the instars, from the one in which the carapace first withdraws from over the eyes and there are no pleopods at all, to that in which there are five setose pleopods, the second antennal endopod is segmented and there is a single terminal and three pairs of postero-lateral spines on the telson. After one pair of postero-lateral spines has been lost the animal is regarded as 'juvenile' or post-larval, until it reaches adult size. This is done because the ecdyses in the juvenile condition (apparently 9 or 10) are orderly and there is no evidence of dominance in any of the stages. In addition the animal may be sexually mature before attaining fully the adult form.

There are twenty-five possible instars in this series. Six are numerically dominant and are regarded as the actual furcilia stages (Fig. 7). This scheme has been followed by most modern workers since it was first suggested by Fraser (1936). Recently, however, Sheard (1953) has proposed an alternative scheme, based mainly on an exhaustive investigation of *Nyctiphanes australis*, in which the number of furcilia stages is reduced to three and the dominants are disregarded. The stages he proposes are as follows:

Furcilia stage 1 (F I). Eyes developed and free of the carapace, pleopods absent or present as non-setose rudiments. Terminal spines (of telson) generally seven. Lateral spines (postero-lateral of telson) three in number, the central spine always present.

Furcilia stage 2 (F II). Some, or all, pleopods setose. Terminal spines sometimes reduced in number, the central spine always present. The pair of long lateral spines unaltered at the base.

Furcilia stage 3 (F III). All pleopods setose and functional. The pair of long lateral spines are altered at the base. The terminal spines are progressively reduced to one (the median spine). The stage terminates with the end of the phase.

The outer limits of Sheard's series are actually the same as those proposed herein for *N. capensis*, or those of *N. simplex* (Boden, 1951), and his F I and F II stages are the same as the first and second furcilia stages presented here. His F III stage, however, embraces the final four furcilia stages of *N. capensis*. Sheard's F II and F III stages are differentiated mainly on the alteration in the shape of the base of the long lateral spines on the telson. This is a somewhat nebulous character, frequently rather difficult to detect, and is not as reliable an indicator as a definite reduction in the numbers of terminal spines on the telson or the sudden change in both form and function of the second antennal endopod.

Sheard 'lumps' the final furcilia stages into his F III stage and throws considerable doubt on the validity of regarding the dominant instars as actual stages and the remainder as variants, on the grounds that the dominants will change from time to time and from place to place. This concept of the dominance of certain instars he regards as a result of the inadequacy of plankton sampling. His arguments are based almost exclusively on the data he obtained for *N. australis* and are applied in an inferential manner to the other species whose development he describes.

It is perfectly true that most plankton sampling is pitifully inadequate, but this cannot be said of Fraser's (1936) work, in which the concept of the dominants constituting the actual stages was originally expressed. His material was spread adequately through time and space and a very large number of individuals was examined. It is also untrue of Einarsson's (1945) work and most of John's (1936).

While the dominants in *Nyctiphanes* may differ (i.e. the modal position may shift) from time to time or place to place they do not appear to move out of the stage boundaries. For example, in *N. capensis* (Fig. 7) it is possible that F III may at times be expressed as a form having seven terminal spines on the telson instead of five (those with six are abnormalities), but the mode will not be absent altogether. Thus, while a false impression may be registered by dogmatically regarding F III as typified by a form having five terminal spines, this impression will probably be less false than that obtained by disregarding all the modes occurring after F II, and considering all the lateral individuals as belonging to one stage.

Sheard states that it is highly probable that any individual will pass through only a limited number of the many possible instars in the stages he proposes. This is undoubtedly true, and it seems only logical that the modes represent the limited number of instars through which the majority of individuals passes and that they can therefore be expressed as stages, and the remainder as variants.

The fact that in *Nyctiphanes* the modes will shift and that by lumping several series of furcilia taken at different times or places one can hide these modes can, perhaps, be explained without doubting that the dominants may be regarded as valid stages.

The genus *Nyctiphanes* is peculiar among the Euphausiacea in that all four known species are shallow-water, neritic forms with limited geographical ranges. *N. simplex* occurs in Californian waters, *N. couchii* in the North Atlantic, *N. australis* in southern Australian and northern New Zealand waters, and *N. capensis* in South African waters. All these species have a great number of variants in their furcilia series and, therefore, substantiate Frost's (1935) claim that species inhabiting coastal waters regularly exhibit greater larval variation than oceanic species. As Sheard points out, the considerable variation exhibited by *Euphausia superba*, generally regarded as an oceanic species, may not controvert this claim, since it inhabits the region of pack ice, which simulates neritic conditions in some respects. The marked reduction in the number of instars in oceanic species has led to some speculation that the Euphausiacea represent arthropods in which gradual development is giving way to metamorphosis. On this premise, the genus *Nyctiphanes* with its great larval variation could be regarded as somewhat more primitive than other genera. It is probable, however, that the large number of variants is not a primitive, but a secondary feature developed during invasion of coastal waters. The genus has several rather specialized features, including an egg-sac in which the first, more vulnerable, larval stages are passed. This, too, is probably a secondary adaptation to the more varied coastal conditions. Thus the genus, in which variation is most marked and the dominant stages are least 'fixed', is one which is specially adapted to a variety of coastal conditions. The fact that dominant instars do occur in any particular place or time can, perhaps, represent the basis for an argument that these instars are an expression of development under the particular environmental conditions obtaining. In other words, such a genus may have slightly different developmental stages under different environmental conditions.

I agree with Sheard that much experimental work with live animals is desirable before the question can be examined much further, but feel that under the present circumstances it is less useful to 'lump' the furcilia stages than to 'split' them. It is possible, unless one is as careful as Sheard has been in giving full codes and counts for all the variants, that much valuable information on development as an expression of environment may be obscured by disregarding dominance. Full data on geographical position, temperature, salinity, oxygen and phosphate content for the stations at which the species reported on herein were taken are available in the *Discovery Report*, vol. XXVI, pp. 211–58.

Furcilia stages

Twenty-five furcilia instars were encountered. If the same terminology is adopted for all four species of *Nyctiphanes* as for *N. simplex* (Boden, 1951), the total number of furcilia types in each species is as follows: *N. couchii* 15, *N. simplex* 16, *N. australis* 24, *N. capensis* 25. For *N. simplex* it was suspected that three other types may occur. Frequency distributions of the *N. capensis* instars are given in Fig. 7.

In the case of *N. simplex* and *N. capensis* six of these types were dominant and are regarded as stages or successive instars, while the remainder are considered variants. According to Gurney (1942) it seems highly probable that there are six stages in *N. couchii* too. While Sheard recognizes only three stages in *N. australis*, it is possible to interpret his data differently. Table 7 shows the course of development of three species of *Nyctiphanes* and it can be seen that they are fairly similar.

Of very great interest is the fact that two of the species do not conform to the rule first shown by Fraser (1936) that the pleopods first appear as non-setose rudiments and these rudiments become setose at the next moult. *N. capensis* and *N. simplex* develop setose pleopods directly in stage II on somites which bore no non-setose rudiments in stage I.

The six stages of *N. capensis* encountered are as follows:

First furcilia. Pleopods non-setose. Second antennal endopod simple.

Second furcilia. Pleopods mixed. Second antennal endopod simple.

Third furcilia. Pleopods setose. Five terminal spines on telson. Second antennal endopod simple.

Fourth furcilia. Pleopods setose. Three terminal spines on telson. Second antennal endopod simple.

Fifth furcilia. Pleopods setose. Three terminal spines on telson. Second antennal endopod segmented.

Sixth furcilia. Pleopods setose. One terminal spine on telson. Second antennal endopod segmented.

First furcilia. Twenty-two specimens examined. Twelve measured (Fig. 8*a–g*). Length range 2·2–2·8 mm.; average length 2·5 mm.

The following types of furcilia are included in this stage. Those with (*a*) no pleopods, (*b*) one pair, (*c*) two pairs, (*d*) three pairs, (*e*) four pairs of non-setose pleopods. No specimens with five pairs of non-setose pleopods were encountered. The occurrence of the above types was as follows: (*a*) 199, (*b*) 35, (*c*) 34, (*d*) 18, (*e*) 6.

There is no rostrum. The frontal plate is broader than long with a small, distinct, emargination of the anterior border. There is a small, but definite, denticle on the inferior margin of the carapace toward the posterior end. The eyes are heavily pigmented and project beyond the edge of the carapace.

The first antennal peduncle has three segments and the basal segment bears a strong spine, reaching just beyond the middle of the third segment, on its anterior outer margin. The rudiments of the two flagella are present on the third segment.

The second antenna is biramous, natatory, and its endopod is simple.

The usual condition of the thoracic appendages is that the first and second maxillae are clearly visible, the first cormopod is present and bifurcate, and the bud of the second cormopod is free but naked. The remaining cormopods are contained in the integument and difficult to discern. Individuals in which the pleopods are developed frequently have the second cormopod present, bifurcate and with bilobed gill rudiments.

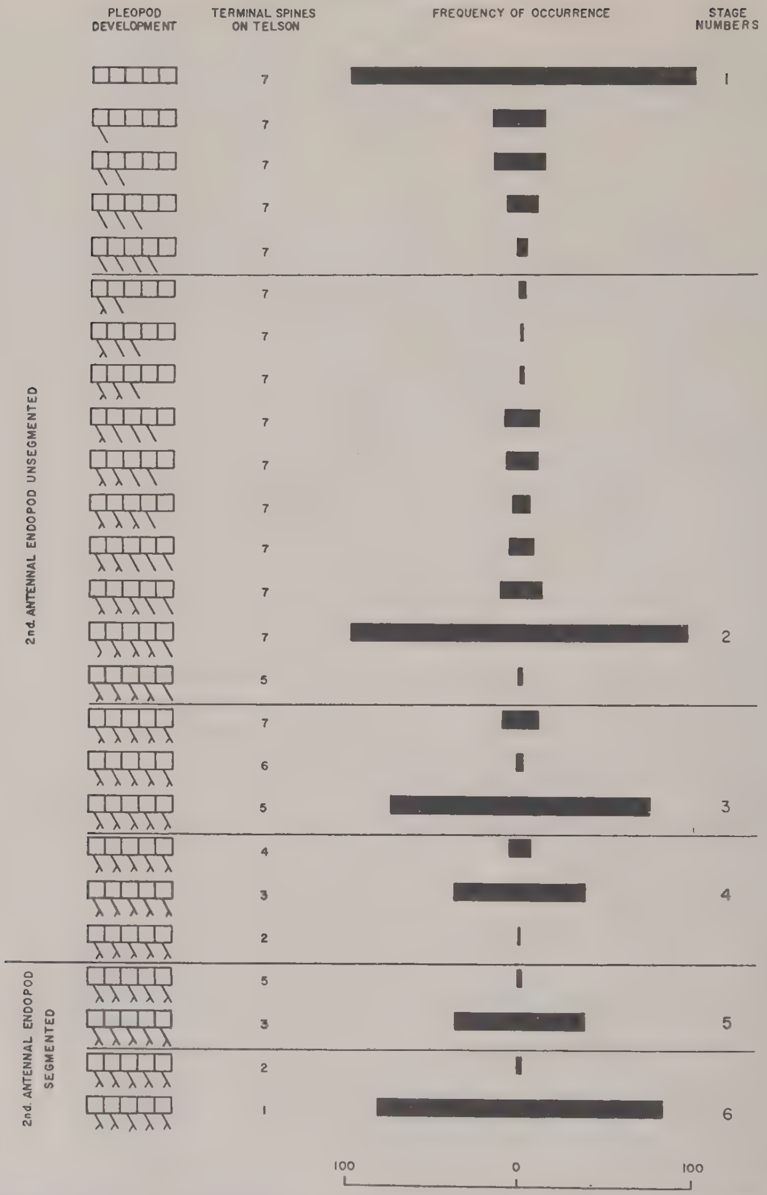

Fig. 7. *Nyctiphanes capensis*. Diagrammatic key to furcilia stages and frequency of occurrence. The rectangles in the left-hand column represent the larval abdomen, each square being an abdominal segment. A simple stroke represents a non-setose pleopod; a feathered stroke represents a setose plopod.

The telson is considerably elongated and the uropods well developed. There is one pair of ventro-lateral spines, three pairs of postero-lateral, and seven terminal spines.

Second furcilia. Nineteen specimens examined (Fig. 8*h–k*). Length range 3·7–4·1 mm.; average length 3·9 mm.

In this stage there are four pairs of setose pleopods and one pair of non-setose.

The types encountered with mixed setose and non-setose pleopods were as follows: (*a*) those with four pleopods: one setose, three non-setose; (*b*) those with four pleopods: two setose, two non-setose; (*c*) those with four pleopods: three setose, one non-setose; (*d*) those with five pleopods: two setose, three non-setose; (*e*) those with five pleopods: three setose, two non-setose; (*f*) those with five pleopods: four setose, one non-setose.

Table 7. *Development of three species of* Nyctiphanes

	Stage 1			Stage 2			Stage 3		
	Pleopods		Telson spines	Pleopods		Telson spines	Pleopods		Telson spines
	N.	S.		N.	S.		N.	S.	
N. capensis	0	0	7	1	4	7	0	5	5
N. simplex	2	0	7	0	5	7	0	5	5
N. couchii	0	0?	7	2	3?	7	0	5?	7

	Stage 4			Stage 5			Stage 6		
	Pleopods		Telson spines	Pelopods		Telson spines	Pleopods		Telson spines
	N.	S.		N.	S.		N.	S.	
N. capensis	0	5	3	0	5	3	0	5	1
N. simplex	0	5	3	0	5	3	0	5	1
N. couchii	0	5	5	0	5	3	0	5	1?

N. = non-setose, S. = setose; stages 5 and 6 have the antennal endopod segmented.
The data for *N. couchii* are taken from Gurney (1942) and those for *N. simplex* from Boden (1951).

Altogether, 286 larvae of this stage were identified in the following numbers: (*a*) 20, (*b*) 19, (*c*) 10, (*d*) 14, (*e*) 28, (*f*) 195. Of these, type (*c*) has previously been reported in the literature only for *Nyctiphanes australis*.

The frontal plate is about as long as it is broad and is somewhat more elongate but still unsegmented.

The second antenna is the same.

The first cormopod is as in the previous stage. The second is bifurcate, segmented, and carries a bilobed gill. The third cormopod is bifurcate, unsegmented, and carries gill rudiments. The remaining cormopods are still bud-like.

The telson has seven terminal spines. The uropods are longer and better developed than in the previous stage.

Third furcilia. Ten specimens examined (Fig. 9*a*-*e*). Length range 4·0-4·4 mm.; average length 4·2 mm.

In this stage there are five setose pleopods, the antennal pleopod is unsegmented and there are (*a*) seven, or (*b*) five terminal spines on the telson. Forty-one specimens of type (*a*) were encountered and one hundred and fifty of type (*b*). Four specimens with six terminal spines were found, each of them abnormal in this respect (Fraser, 1936; John, 1936).

The frontal plate is longer than it is broad and its anterior margin is concave.

The flagella of the first antenna are elongate but unsegmented.

The second antenna is still natatory and both rami are unsegmented.

The endopod of the first cormopod is longer than the exopod and has three segments.

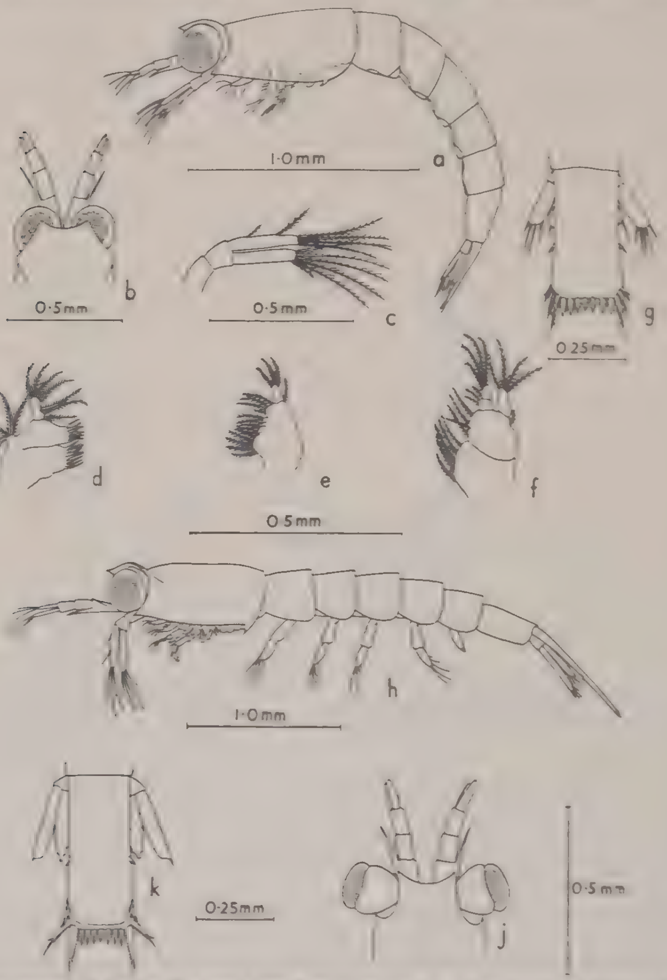

Fig. 8. *Nyctiphanes capensis*. *a*, first furcilia, lateral view; *b*, cephalothorax, dorsal view; *c*, second antenna; *d*, first maxilla; *e*, second maxilla; *f*, first cormopod; *g*, telson of first furcilia; *h*, second furcilia, lateral view; *j*, cephalothorax, dorsal view; *k*, telson of second furcilia.

The second cormopod is well developed: the endopod is long, has five segments, with a strong knee. There is a gill, with two branches, at the base of the exopod.

The endopod of the third cormopod is shorter than the second and is feebly kneed. The gill has two unequal branches. The fourth endopod is shorter than the third, has three segments and is straight. The gill has two branches. The fifth cormopod is short, bifurcate, non-setose with two gill buds.

The remaining cormopods are short, simple buds.

The pleopods are all biramous and setose.

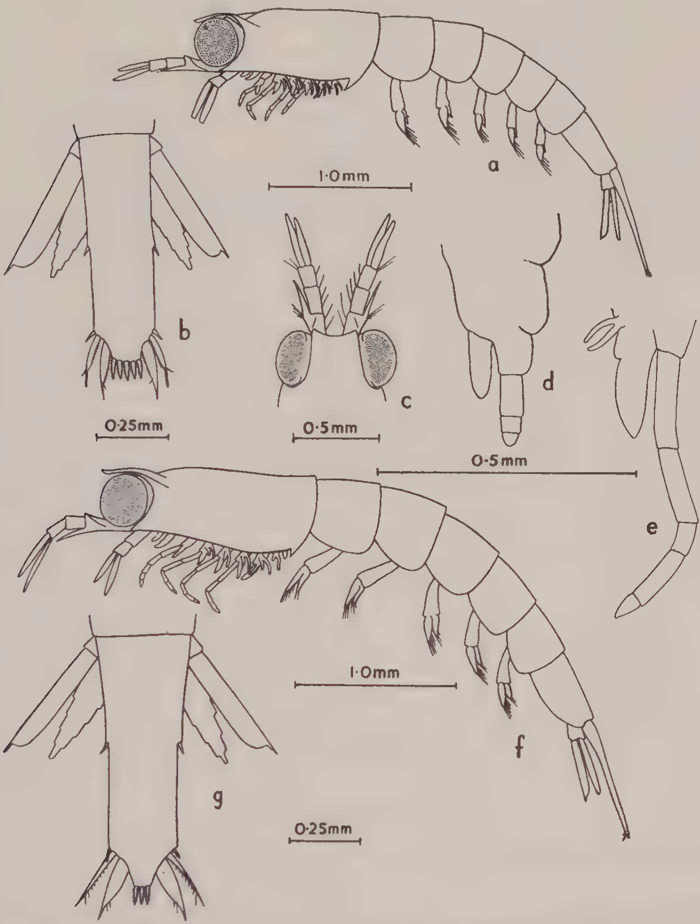

Fig. 9. *Nyctiphanes capensis*. *a*, third furcilia, lateral view; *b*, telson of same; *c*, cephalothorax, dorsal view; *d*, first cormopod; *e*, second cormopod; *f*, fourth furcilia, lateral view; *g*, telson of same.

The number of terminal spines on the telson is reduced to five. The innermost pair of postero-lateral spines is the sturdiest and longest, and has a wide base.

Fourth furcilia. Fifteen specimens examined (Fig. 9*f*, *g*). Length range 4·3–4·6 mm.; average length 4·4 mm.

The second antennal endopod is still simple in this stage but the number of terminal spines on the telson is reduced to three. Twelve with four spines and one with two spines were also found.

The carapace, frontal plate and eyes remain unaltered.

The flagella of the first antenna are still unsegmented and the second antenna remains natatory and unsegmented.

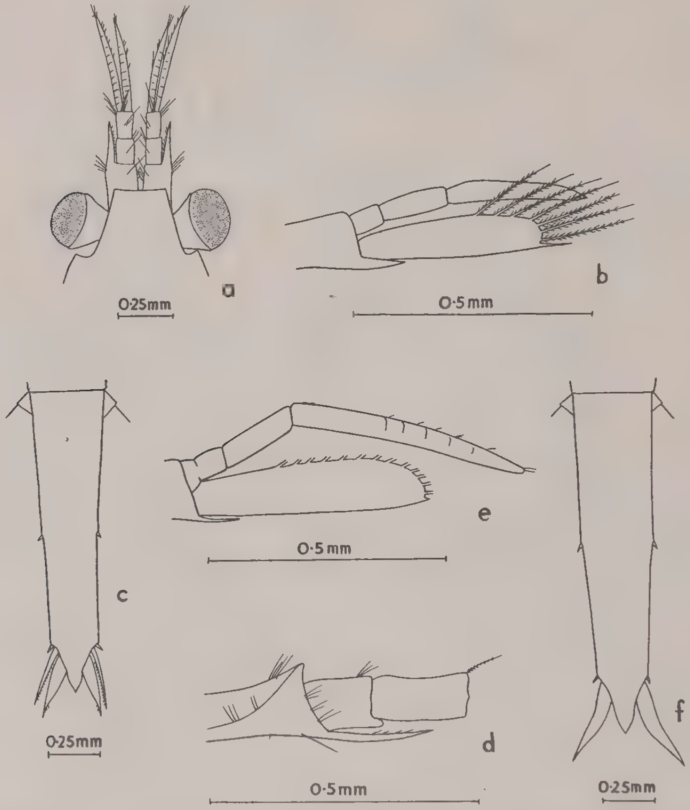

Fig. 10. *Nyctiphanes capensis*. *a*, fifth furcilia, cephalothorax in dorsal view; *b*, second antenna; *c*, telson; *d*, sixth furcilia, peduncle of first antenna; *e*, second antenna; *f*, juvenile telson.

The first four cormopods have their full complement of segments; the first is feebly kneed, the second to the fourth powerfully so. The fifth cormopod is unaltered and the remainder are rudimentary.

The telson still carries three pairs of postero-lateral spines and three terminal spines.

Fifth furcilia. Thirteen specimens examined (Fig. 10*a–c*). Length range 4·5–4·9 mm.; average length 4·7 mm.

The number of terminal spines on the telson remains three, although two specimens were encountered with five terminal spines on the telson.

The carapace retains the lateral denticle and is unaltered except for the frontal plate, which is no longer as concave as formerly. The eyes are the same.

The flagella of the first antenna are setose and segmented.

The second antenna has a segmented non-setose flagellum, and a scale which is setose terminally and along the anterior third of its inner border.

The cormopods are the same as in the previous stage, except that the fifth is now jointed, but still non-setose.

Sixth furcilia. Twenty-one specimens examined (Fig. 10*d*, *e*). Length range 4·8–5·3 mm.; average length 5·1 mm.

The terminal spines on the telson are reduced to one in number. Three abnormal specimens with two terminal spines occurred.

The frontal plate is a trifle narrower than in the previous stage, but the carapace is otherwise unaltered. The tooth on the lateral margin remains. In *N. simplex*, it has disappeared at this stage.

The basal segment of the first antennal peduncle shows the rudiments of the adult reflexed lappet on its upper, distal margin. The spine on its outer margin reaches just beyond the middle of the third segment.

The flagellum of the second antenna has a base with three segments and it reaches beyond the scale for about half its own length. The scale bears setae all along its inner margin and a spine at its base on the outside.

The endopodite of the sixth cormopod is now jointed but that of the seventh is still unjointed. The luminous organ is present at the base of the seventh cormopod.

Juveniles (Fig. 10*f*). Once the outer, long, lateral spines on the telson are lost, the animal is classed as juvenile. It appears to undergo about nine or ten moults before assuming a fully adult form. In the course of this development the cormopods become jointed and geniculate, the frontal plate diminishes and becomes adult in appearance, and the lateral denticle on the carapace disappears. There appears to be considerable individual variation in the development of these characteristics. There is no evidence of dominance in the juvenile series.

Euphausia lucens Hansen

Egg. 0·38–0·40 mm. in formalin (Fig. 11*a*).

Five eggs were found and measured. They appeared to be on the verge of hatching, for all contained well-developed nauplii. The nauplius completely fills the egg-case at this stage.

Nauplius. No free nauplii were found. Those within the egg had three pairs of appendages—uniramous first antennae, biramous second antennae and biramous mandibular palps. The first antenna carries a single terminal spine. Each ramus of the remaining appendages is armed with three spines (Fig. 11*a*).

Pseudometanauplius. This stage was not represented in the material.

Metanauplius. Only one specimen of this stage was found (Fig. 11*b*, *c*).

The length of the carapace is about 0·4 mm. There is a large, elaborately serrated rostral hood.

The first antenna is uniramous and carries three spines.

The second antenna is biramous, the rami being armed with four and five spines respectively. The exopod is segmented distally.

The mandibular palp is reduced to a small papilla.

The unarmed limbs of the metanauplius are partially covered by folds in the carapace.

The telson is differentiated and carries eight spines.

First calyptopis. Five specimens examined (Fig. 12*a*–*c*). Length range 0·98–1·1 mm.; average length 0·99 mm.

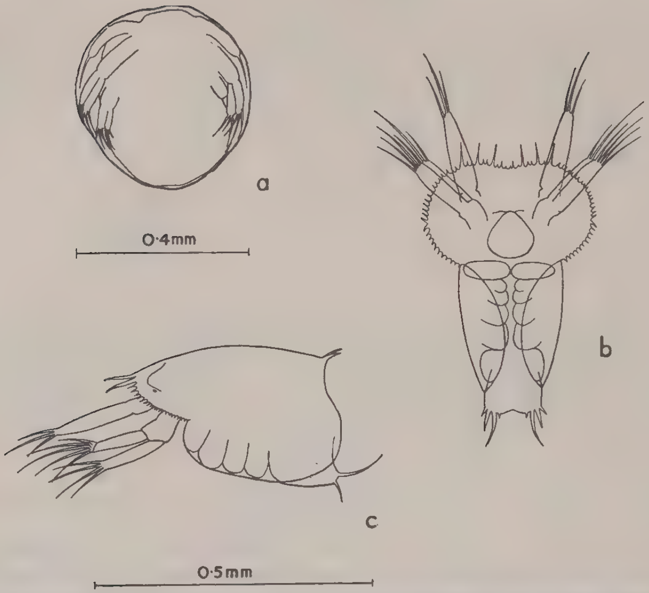
a
0·4mm
b
c
0·5mm

Fig. 11. *Euphausia lucens*. *a*, egg on verge of hatching; *b*, metanauplius in ventral view; *c*, metanauplius in lateral view.

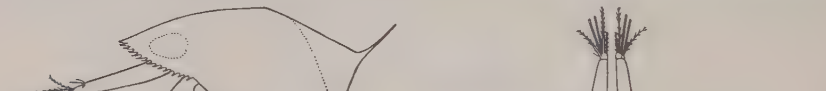
a
0·5mm
b
0·25mm
c
0·5mm

Fig. 12. *Euphausia lucens*. *a*, first calyptopis, lateral view; *b*, distal part of telson; *c*, first calyptopis, dorsal view.

The carapace is domed and the posterior margin is produced as a sharp, upward-pointing spine. The anterior margin of the carapace fans out as a serrated rostral hood. There are no lateral denticles on the inferior margin of the carapace.

The ocular plates can be seen and the median eye is present.

A rudimentary inner ramus, carrying two setae, can be seen on the forward-pointing first antenna. The outer ramus carries four setae, two of which are sensory.

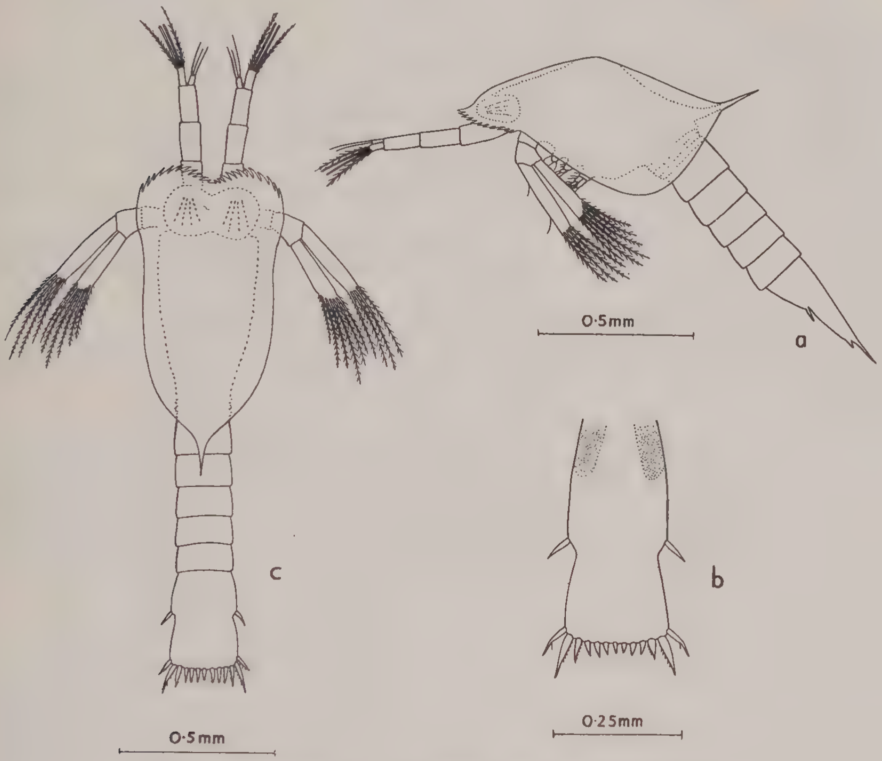

Fig. 13. *Euphausia lucens.* *a*, second calyptopis, lateral view; *b*, telson of same; *c*, second calyptopis, dorsal view.

The second antennal peduncle has two segments, and the antenna is biramous. The anterior ramus carries four setose terminal spines and two lateral spines. The second ramus carries six setose terminal spines.

The first and second maxillae and first thoracic limb are present and setose.

The limbless thoracic segments can be discerned as wrinkles in the integument.

There is no sign of segmentation in the abdomen. The telson is armed with one pair of ventro-lateral spines, three pairs of postero-lateral spines and six terminal spines. The innermost pair of postero-lateral spines resembles the terminal spines more closely than in other euphausiids at this stage, and as a result the telson looks as though it has eight terminal spines.

Second calyptopis. Seven specimens examined (Fig. 13*a–c*). Length range 1·3–1·8 mm.; average length 1·6 mm.

The rostral hood is not as conspicuous as in the preceding stage, although its anterior margin is still serrated. The posterior margin of the carapace is still produced as a sharp spine.

There is no sign of the median eye and the compound eyes are now quite clearly defined.

The biramous first antenna is carried on a peduncle of three segments. The outer ramus carries four setae and the inner three.

The second antenna and remaining thoracic appendages are unchanged.

The thoracic segmentation is clearly visible.

There are now five segments and a telson to the abdomen and the rudimentary uropods can be seen within the integument of the telson. The ventro-lateral and postero-lateral spines of the telson are retained, but there are now seven terminal spines.

Third calyptopis. Five specimens examined (Fig. 14*a–c*). Length range 2·10–2·33 mm.; average length 2·24 mm.

The anterior margin of the rostral hood is serrated and the posterior margin of the carapace is produced as a sharp, dorsal spine. The inferior margin of the carapace has developed a small denticle toward its posterior end.

The globular compound eyes are pigmented and covered by the rostral hood.

On the outer distal margin of the basal segment of the first antennal peduncle is a strong toothed spine reaching nearly to the end of the third segment. The spines on the two rami of the first antennae are unchanged.

There is no alteration in the second antennae or the remaining thoracic appendages.

The abdomen has six segments and a telson. The six segments are naked but the lateral uropods of the telson have developed and are spinose. The outer ramus of the uropod has its outer margin produced as a small tooth. It carries six spines. The inner ramus carries four. There are three pairs of postero-lateral spines and seven terminal spines on the telson. The central terminal spine is much reduced and the remaining three pairs are turned toward it.

Furcilia stages. Six furcilia stages of *E. lucens* were found and they are as follows:

Table 8. *Furcilia stages of* Euphausia lucens

Stage 1			Stage 2			Stage 3			Stage 4			Stage 5			Stage 6		
Pleopods		Telson spines	Pleopods		Telson spines	Pleopods		Telson spines	Pleopods		Telson spines	Pleopods		Telson spines	Pleopods		Telson spines
N.	S.		N.	S.		N.	S.		N.	S.		N.	S.		N.	S.	
1	—	7	4	1	7	—	5	7	—	5	5	—	5	3	—	5	1

N. = non-setose, S. = setose; stages 5 and 6 have the second antennal endopod segmented.

Specimens found: stage 1=6, stage 2=3, stage 3=5, stage 4=2, stage 5=6, stage 6=8.

While this paper was being prepared it was necessary to move the collection on which it is based from Bermuda to California. This was done by Military Air Transport and despite the most careful packing and rigorous precautions, the tubes containing the furcilia stages of *E. lucens* were broken and most of the contents were lost. Only four of the thirty specimens were salvaged and these belong to the first two stages. For these reasons, descriptions and illustrations of the first two stages only are presented here. It was possible to give the diagnostic characters of the later stages in Table 8 from laboratory notes made at the time of sorting.

First furcilia. Six specimens were found and one was measured and examined (Fig. 15*a*–*g*). The length was about 3 mm.

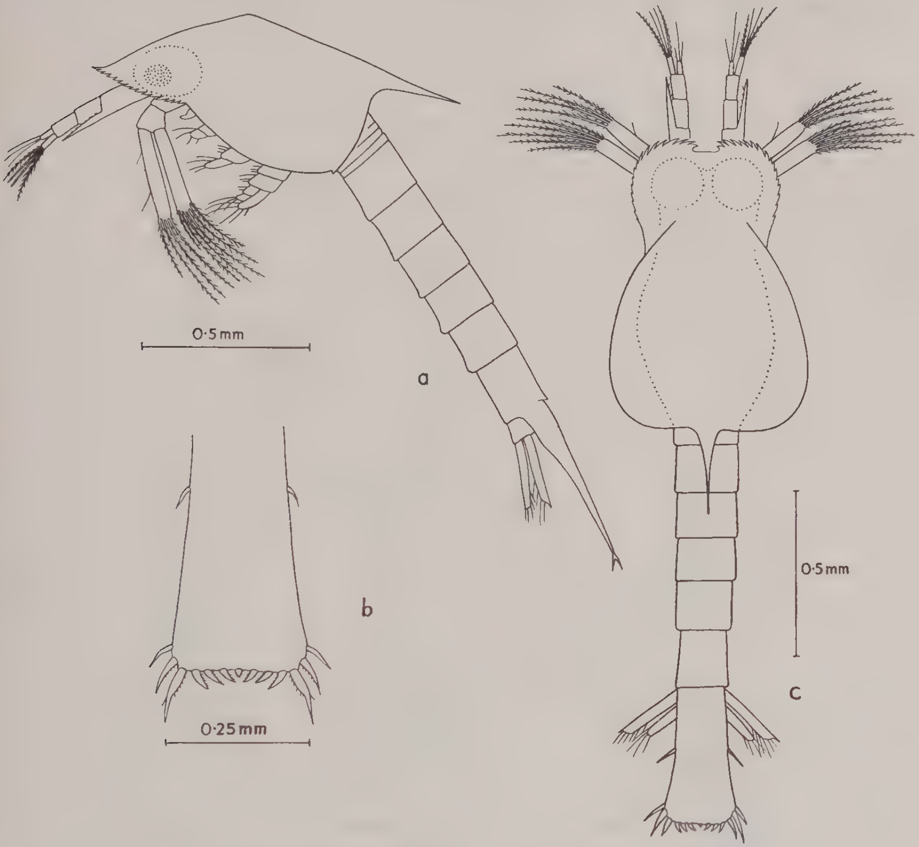

Fig. 14. ***Euphausia lucens.*** *a*, third calyptopis, lateral view; *b*, telson of same; *c*, third calyptopis, dorsal view.

The anterior margin of the carapace is serrated and the frontal plate is broader than long. The posterior margin of the carapace is slightly produced as a dorsal spine and there is a conspicuous denticle on the inferior margin toward the posterior end.

The pigmented eyes are no longer covered completely by the carapace.

The basal segment of the first antennal peduncle bears, on its outer margin, a strong toothed spine reaching to the end of the third segment. The two rudimentary flagella are present on the third segment and they bear three and four spines respectively.

The natatory, biramous second antenna carries a simple endopod.

The first and second maxillae are visible and the bifurcate first cormopod is present.

The first segment of the abdomen bears one pair of non-setose pleopods.

The telson is elongated and the uropods are well developed. The telson carries seven terminal spines, three pairs of postero-lateral and one pair of ventro-lateral spines.

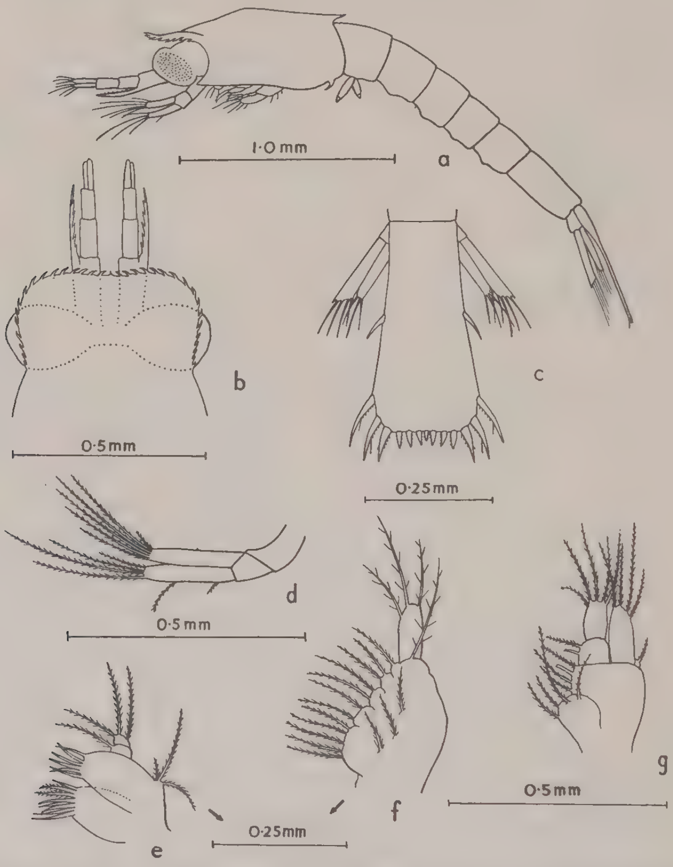

Fig. 15. *Euphausia lucens*. *a*, first furcilia, lateral view; *b*, cephalothorax, dorsal view; *c*, telson and lateral uropods; *d*, second antenna; *e*, first maxilla; *f*, second maxilla; *g*, first cormopod.

Second furcilia. Three specimens were found (Fig. 16*a*, *b*). The average length was 3·5 mm.

The anterior margin of the carapace has narrowed to a finely serrated frontal plate. The posterior margin is no longer produced as a dorsal spine, but the inferior margin retains its denticle.

The rather small eyes project considerably beyond the margins of the frontal plate.

The first and second antennae are unchanged.

The remaining thoracic appendages are the same as in the preceding stage except that the second cormopod has appeared and bears small gill lobes.

The abdomen bears one setose and four non-setose pairs of pleopods.

The condition of the telson remains unchanged.

Remaining stages. The diagnostic characters of the remaining stages are given in Table 8.

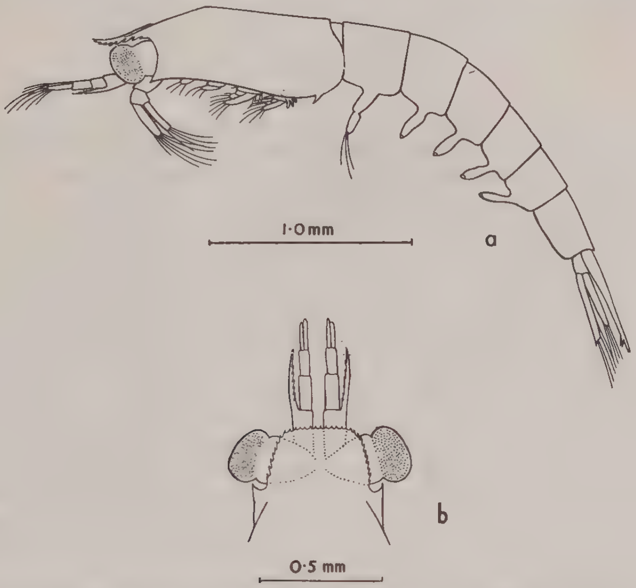

Fig. 16. *Euphausia lucens. a*, second furcilia, lateral view; *b*, cephalothorax, dorsal view.

As the animal approaches the adult form the frontal plate becomes smaller and loses its serrations. In the adult phase this plate is a low triangle somewhat broader than long. It may or may not carry a rudimentary rostrum.

The lateral denticle on the carapace moves gradually forward from its posterior position until it reaches about the middle of the inferior margin.

The upper distal margin of the basal segment of the first antennal peduncle becomes progressively more produced until it is an acute, triangular lobe. A keel appears on the upper surface of the third segment.

In the fifth and sixth stages the second antenna loses its natatory function and the endopod becomes segmented.

Euphausia tenera Hansen

It was not possible to identify any pre-furcilia stages of this species.

Five furcilia stages of *E. tenera* were found in the plankton and are presented in Table 9. It seems highly probable that a sixth stage, with only a single terminal spine on the telson, also occurs, although it was not encountered.

Table 9. *Furcilia stages of* Euphausia tenera

Stage 1			Stage 2			Stage 3			Stage 4			Stage 5			Stage 6		
Pleopods		Telson spines	Pleopods		Telson spines	Pleopods		Telson spines	Pleopods		Telson spines	Pleopods		Telson spines	Pleopods		Telson spines
N.	S.		N.	S.		N.	S.		N.	S.		N.	S.		N.	S.	
3	1	7	1	4	7	—	5	7	—	5	5	—	5	3	—	5	1

N. = non-setose, S. = setose.

Specimens found: stage 1 = 5, stage 2 = 1, stage 3 = 4, stage 4 = 20, stage 5 = 3, stage 6 = 0.

Lebour (1949) has described three stages (the first three) of *E. tenera* from Bermuda. The first of these carries one non-setose pleopod, the second four non-setose and one setose and the third five setose. Only the third of these stages occurred in the series presented here.

The larvae examined during this inquiry were considerably larger than those described by Lebour (*E. tenera* is a small species) and in the first stages the state of development of the cormopods and pleopods was relatively advanced.

My material was preserved, and positive identification was therefore more difficult. However, these larvae occurred in the same tows as adult *E. tenera* and later stages resembled the adult phase of *E. tenera* (particularly in the shape of the rostrum) more closely than that of any other euphausiid present. They conform closely to Lebour's descriptions and illustrations and the similarity in the shape of the rostrum is most marked. The explanation of the discrepancies in the earlier stages may lie in inadequate sampling (only thirty-three specimens were present in this material), and the first two stages described by Lebour are, therefore, the real stages. Another possible explanation of the large size and advanced condition of development may be found in the environmental differences encountered in the Benguela Current and the Bermuda waters. The Benguela Current is a cold, upwelling current with waters rich in nutrient salts, whereas the warm oceanic waters of the north-western Sargasso are notoriously poor in nutriment.

First furcilia. Five specimens examined and measured. Length range 4·0–4·4 mm.; average length 4·2 mm. (Fig. 17*a–j*).

The frontal plate of the carapace is rounded and comes to a sharp point in the centre of the anterior margin. The margin is otherwise quite smooth. The inferior margin of the carapace carries a small denticle toward the posterior end. Its posterior margin lacks a dorsal spine.

There are three segments to the first antennal peduncle and the basal segment carries, on its outer distal margin, a strong-toothed spine which extends to just beyond the distal end of the third segment. The third segment carries two rudimentary flagella.

The second antenna is biramous and natatory. The simple endopod carries four setose spines terminally and the exopod carries seven.

The first and second maxillae are visible. The first and second cormopods are present and bifurcate and the second carries rudimentary gill-lobes. The third is present as a naked, simple bud.

The first abdominal segment carries a pair of setose pleopods and the following three carry non-setose pleopods.

The well-developed telson carries well-developed uropods. It is armed with one pair of ventro-lateral, three pairs of postero-lateral, and seven terminal spines.

Second furcilia. One specimen examined and measured. Length 4·9 mm. (Fig. 18*a*, *b*).

The anterior margin of the frontal plate is somewhat less pointed than in the preceding stage.

The thoracic appendages are unchanged except for the cormopods. The second is now segmented and geniculate. The third is bifurcate and carries rudimentary gills. The fourth is now visible as a simple bud bearing rudimentary gill-lobes.

The abdomen bears four pairs of setose pleopods and one pair of non-setose.

The condition of the telson is unchanged.

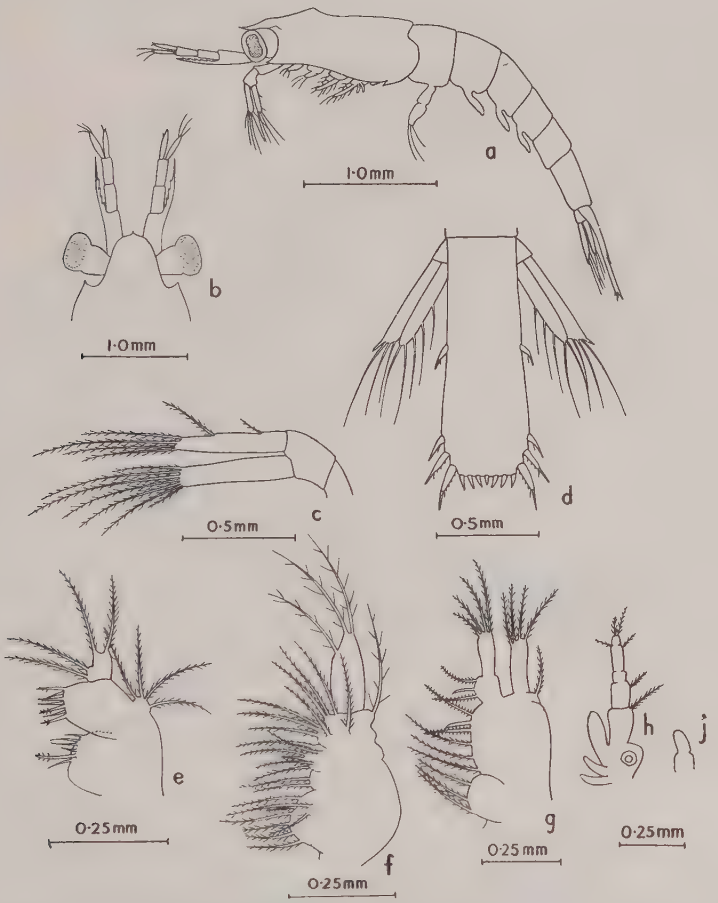

Fig. 17. ***Euphausia tenera.*** *a*, first furcilia, lateral view; *b*, cephalothorax, dorsal view; *c*, second antenna; *d*, telson and uropods; *e*, first maxilla; *f*, second maxilla; *g*, first cormopod; *h*, second cormopod; *j*, third cormopod.

Third furcilia. Four specimens examined and measured. Length range 5·1–5·3 mm.; average length 5·2 mm. (Fig. 18*c*, *d*).

The anterior margin of the carapace is now produced as a definite, pointed rostrum which extends beyond the eyes.

The endopod of the third cormopod is now segmented and geniculate. The fourth cormopod is bifurcate and the fifth is present as a simple bud. The second to fifth cormopods bear gill-lobes.

All five pairs of pleopods are now setose.

The telson remains the same and still carries seven terminal spines.

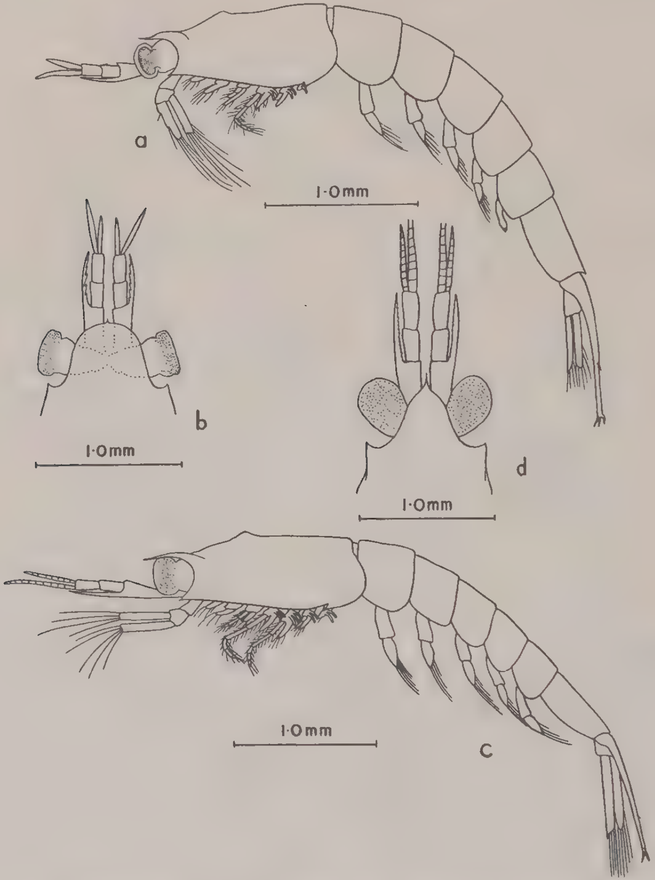

Fig. 18. *Euphausia tenera*. *a*, second furcilia, lateral view; *b*, cephalothorax, dorsal view; *c*, third furcilia, lateral view; *d*, cephalothorax, dorsal view.

Fourth furcilia. Twenty specimens present. Seven examined and measured. Length range 5·3–5·7 mm.; average length 5·5 mm. (Fig. 19*a*, *b*).

The rostrum is a trifle more pronounced, but otherwise unchanged.

The flagella of the first antennae are elongated and segmented.

The endopod of the fourth cormopod is now segmented and geniculate. The fifth is bifurcate and the sixth is present as a simple bud. The second to the sixth bear gill-lobes, those on the sixth being more arborescent than those on the more anterior cormopods.

The pleopods are all setose.

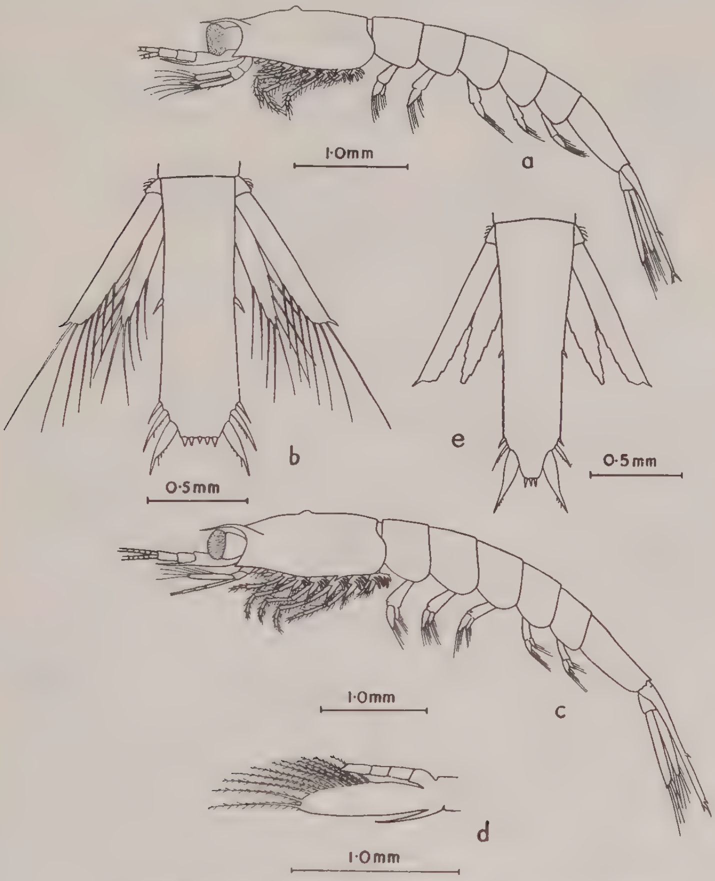

Fig. 19. *Euphausia tenera*. *a*, fourth furcilia, lateral view; *b*, telson and uropods; *c*, fifth furcilia, lateral view; *d*, second antenna; *e*, telson and uropods.

The number of terminal spines on the telson is now reduced to five. There are still three pairs of postero-lateral and one pair of ventro-lateral spines. The lateral uropods are now strongly developed.

Fifth furcilia. Three specimens present. All examined and measured. Length 6·3 mm. (Fig. 19*c*, *d*, *e*).

The second antenna is no longer natatory. The endopod is segmented and the exopod is scale-like with a strong tooth situated proximally at the outer margin.

The sixth cormopod is now bifurcate and carries a complex gill structure.

The two outer pairs of postero-lateral spines on the telson are much reduced while the inner pair has increased considerably in size.

The number of terminal spines has been reduced to three.

Nematoscelis megalops G. O. Sars

Egg. 0·41–0·43 mm. in formalin (Fig. 20*a*, *b*).

There is a moderately large perivitelline space between the egg contents and the thin, transparent membrane. Just before hatching the first nauplius can be clearly seen, and it now completely fills the interior of the egg-capsule.

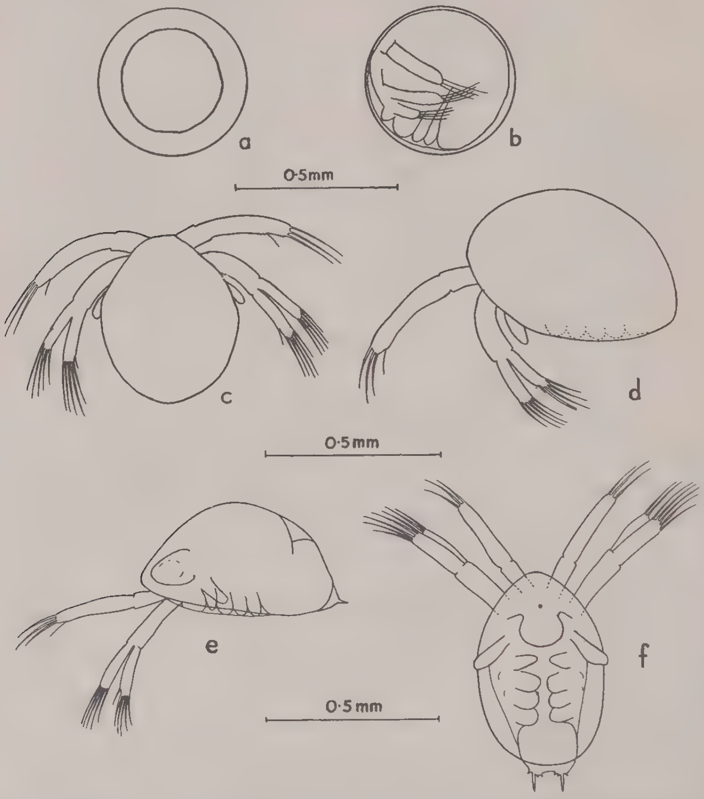

Fig. 20. *Nematoscelis megalops*. *a*, egg; *b*, egg containing nauplius prior to hatching; *c*, nauplius, dorsal view; *d*, nauplius, lateral view; *e*, pseudometanauplius, lateral view; *f*, pseudometanauplius, ventral view.

Nauplius. 0·43–0·53 mm. Six specimens examined (Fig. 20*c*, *d*).

The body is round-oval in dorsal aspect with no appendages or processes at the posterior end.

The first antennae are uniramous, with four setae.

The second antennae are biramous, the branches having five and six setae respectively.

The mandibles are uniramous and naked.

The rudiments of the metanaupliar limbs are discernible through the skin.

Pseudometanauplius. 0·53–0·57 mm. Five specimens examined (Fig. 20*e*, *f*).

The body is more elongated than in the previous stage, oval, and at the posterior end the rudimentary telson can be seen.

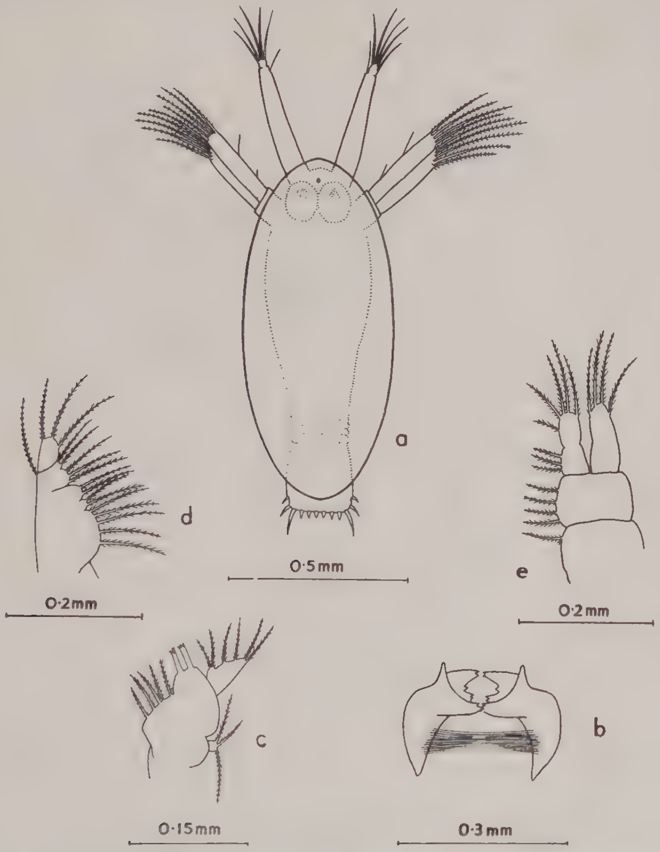

Fig. 21. *Nematoscelis megalops.* *a*, first calyptopis, dorsal view; *b*, mandible; *c*, first maxilla; *d*, second maxilla; *e*, first thoracic limb.

The antennae project forward, but are otherwise unchanged.

The median eye and the rudiments of the ocular plates are visible.

There are two to four pairs of spines at the end of the rudimentary telson.

The carapace, metanaupliar limbs, and telson are encased in an extremely thin, transparent skin.

Metanauplius. No metanaupliar stages were encountered.

First calyptopis. Seven specimens examined (Fig. 21 *a–e*; Fig. 22 *a*, *b*). Length range 0·97–1·0 mm.; average length 0·98 mm.

The carapace is a long, high and very narrow dome which covers the entire anterior part of the body. There are no denticles on the inferior margin.

The ocular plates are visible and the median eye is still present.

The first antennae project forward. The rudiments of an inner ramus can be seen bearing two or three setae. There are five naked terminal setae on the outer ramus.

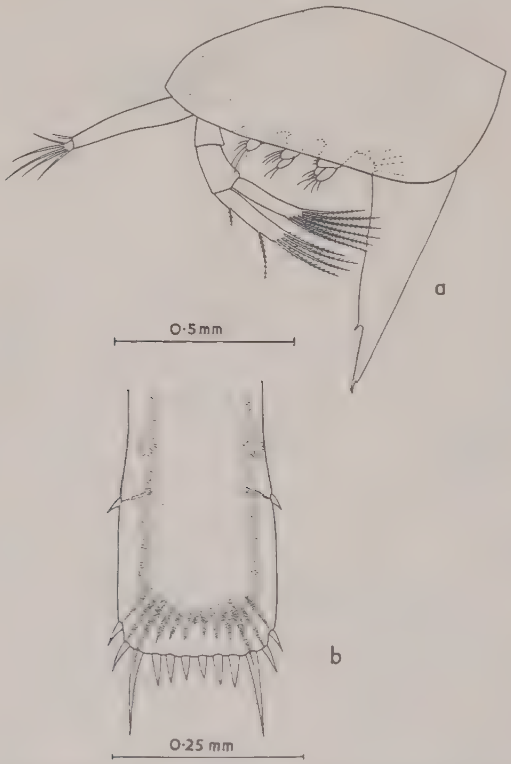

Fig. 22. *Nematoscelis megalops*. *a*, first calyptopis, lateral view; *b*, telson. The form of the telson of the succeeding instar is visible through the skin.

The two rami of the second antennae are carried on a peduncle of two segments. The anterior ramus carries two lateral spines and four setose terminal spines. The second ramus carries six setose terminal spines.

The mandible is naked, and the first and second maxillae and first thoracic limb are present and setose.

The abdomen is unsegmented. The telson carries one pair of ventro-lateral, three pairs of postero-lateral, and six terminal spines.

Second calyptopis. Five specimens examined (Fig. 23*a–c*). Length range 1·6–2·0 mm.; average length 1·7 mm.

The carapace is unchanged except for its posterior margin which has a small, smooth projection in the middle.

The compound eyes and ocular luminous organ are defined, but the median eye is lost.

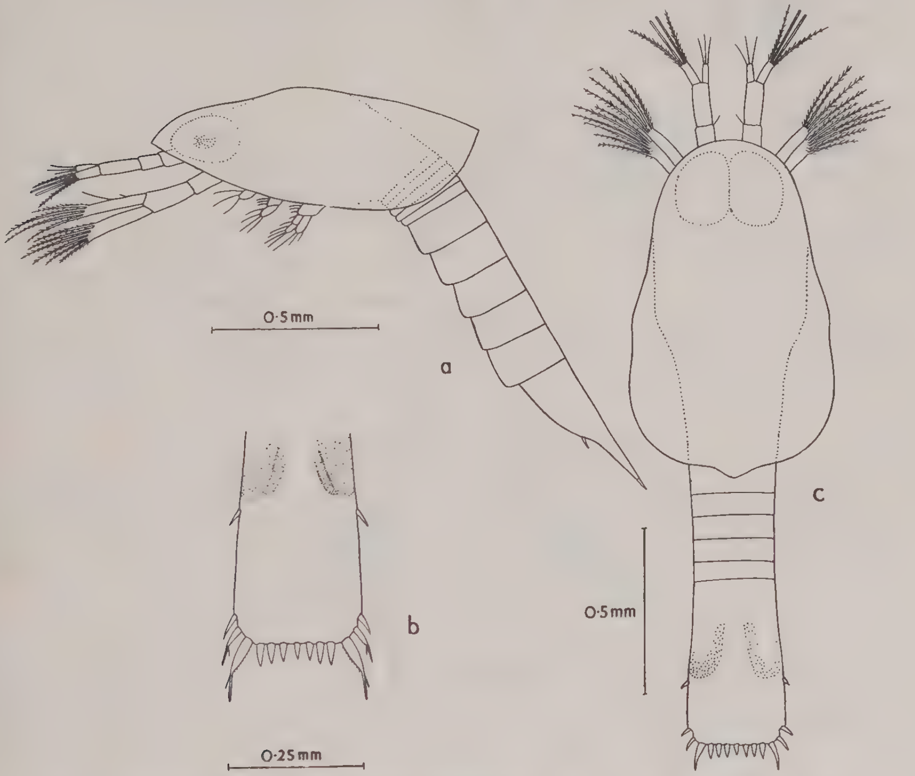

Fig. 23. *Nematoscelis megalops*. *a*, second calyptopis, lateral view; *b*, telson; *c*, second calyptopis, dorsal view.

The first antenna is biramous and has a three-segmented peduncle. The inner ramus carries three terminal setae and the outer ramus four. The second segment of the peduncle carries a small spine on its inner, distal margin.

The remaining thoracic appendages are the same as in the first calyptopis except that the endopodite of the first cormopod now has two segments. In none of the five specimens examined was there any sign of the second thoracic limb. The thorax is clearly segmented.

The abdomen has five segments and a telson. The developing uropods can be very clearly discerned within the integument of the telson. The telson now carries seven terminal spines, three pairs of postero-lateral and one pair of ventro-lateral.

Third calyptopis. Eleven specimens examined (Fig. 24*a*, *b*). Length range 2·4–2·9 mm.; average length 2·7 mm.

The carapace is unchanged except for the appearance of the rudiments of the dorsal crest. The inferior margin is smooth.

The compound eyes are globular and pigmented.

The basal segment of the first antennal peduncle bears a strong toothed spine on its outer, distal margin. This reaches to about the middle of the last peduncular segment.

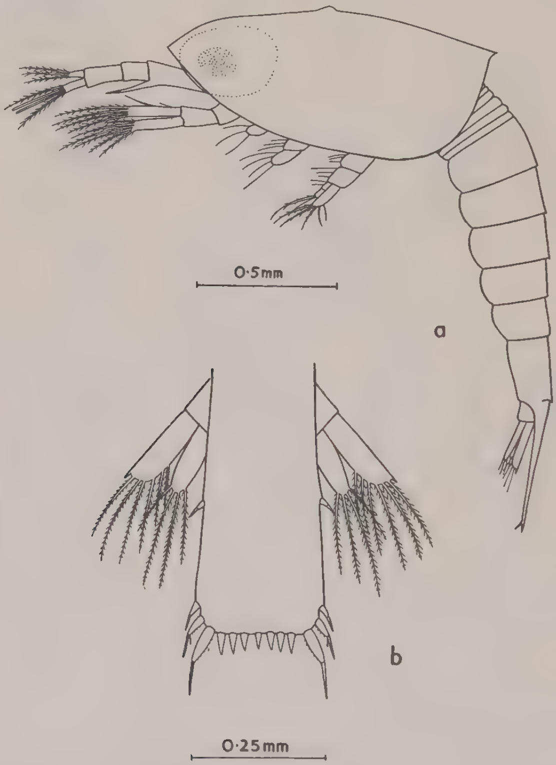

Fig. 24. *Nematoscelis megalops.* *a*, third calyptopis, lateral view; *b*, telson and uropods.

The second antennae and thoracic appendages have not changed.

There are now six abdominal segments and a telson. The abdomen bears no appendages.

The lateral uropods of the telson are now developed and spinose. The outer ramus of the uropod is somewhat longer than the inner and its outer margin is produced as a small, strong tooth. The remaining armature of the telson is unchanged.

A dorsal view of this stage can be seen in Frost (1935), and is, therefore, not figured here. She does not, however, indicate the small, smooth projection on the posterior margin of the carapace. This can be seen even in lateral view.

Furcilia stages. Frost (1935) has already described one calyptopis, three furcilia and four cyrtopia stages for this species. The calyptopis was a third calyptopis and she called the three furcilia the third, eighth and penultimate. The cyrtopia were the first to the fourth inclusive.

Gurney (1942) considers Frost's furcilia stages to be the first, second and third furcilia. Undoubtedly her 'third' and 'eighth' furcilia are in reality the first and second stages respectively, for no preceding or intermediate forms have ever been found. In the present series, however, a form intermediate between Frost's eighth and penultimate furcilia occurs. This form has five setose pleopods and seven terminal spines on the telson. Only one specimen was found, but it is considered here as the third furcilia stage.

Frost's penultimate furcilia had the telson spines reduced to five. This now becomes the fourth furcilia stage. Frost considered that this stage was not the immediate precursor of the first cyrtopia, for in all other cases of euphausiid development there are two stages with only one terminal telson spine; in the first stage the long, outer laterals are present and in the second they are absent. She thought it highly probable that one or more stages exist between her penultimate furcilia and first cyrtopia. In this she was quite right, for one specimen was found in this series having one terminal telson spine and still retaining the long, outer laterals.

I have called this the sixth furcilia, however, rather than the fifth. If it were the fifth the number of terminal spines would have to be reduced from five to one in one stage. This sequence has never been reported in any other euphausiid life-history and it seems justifiable to suspect that there is at least one stage with three terminal spines on the telson. The furcilia stages then are as follows:

Table 10. *Furcilia stages* of Nematoscelis megalops

Stage 1			Stage 2			Stage 3			Stage 4			Stage 5			Stage 6		
Pleopods		Telson spines	Pleopods		Telson spines	Pleopods		Telson spines	Pleopods		Telson spines	Pleopods		Telson spines	Pleopods		Telson spines
N.	S.		N.	S.		N.	S.		N.	S.		N.	S.		N.	S.	
2	—	7	3	2	7	—	5	7	—	5	5	—	5	3?	—	5	1

N. = non-setose, S. = setose; stages 5 and 6 have the second antennal endopod segmented.

The numbers of specimens in each stage in this series are as follows: stage 1 = 28, stage 2 = 48, stage 3 = 1, stage 4 = 9, stage 5 = 0, stage 6 = 1.

Frost's descriptions and illustrations are accurate and adequate and it is considered unnecessary to elaborate on them.

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Contribution from the Scripps Institution of Oceanography, New Series No.785

PARTICLE SIZE DISTRIBUTION IN NEARSHORE SEDIMENTS

BY

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PARTICLE-SIZE DISTRIBUTION IN NEARSHORE SEDIMENTS[1]

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ABSTRACT

The patterns of the areal variation in the distribution of sediments from several beach and nearshore environments along the California and Gulf of Mexico coasts have been studied. A detailed investigation was conducted on a closely-spaced grid in one of the areas, and sufficient areal and seasonal samples were obtained so that the characteristics of the distribution of particle size with time and distance could be determined. In general it was found that seasonal changes in the sediments were not of sufficient magnitude to overshadow properties that can be attributed to the location or environment of deposition of the sediment. The investigation also indicated that delineations of the various sediment types were facilitated by a technique in which three size distribution parameters were plotted as variables: the median diameter, a measure of sorting (deviation), and a measure of skewness.

The findings and techniques from the control area which was studied in detail were applied in more complex localities such as the embayments along the Texas coast and in the Mississippi delta region. Several types of sediment were established on a basis of particle-size distribution, and in general it was found that these types were characteristic of the environments of deposition. For example, the beach sands were found to be among the coarsest and best sorted material in each area, while samples from localities where two distinct sediment types mix, showed a pronounced positive skewness and were poorly sorted.

INTRODUCTION

The purpose of the investigation was to study the particle-size distributions of sediments in nearshore environments, and to determine the nature of the sediments which are deposited as a result of different transporting processes and different amounts and type of sediment supply. Statistical measures were adapted to the size-frequency distribution of sediments, and each sediment was described in terms of a measure of central tendency, sorting, and skewness. The character of the distributions of the sediments in a given environment was obtained by considering these measures as tri-variate functions and plotting their projection on two planes. In this way, the variations and distributions of large groups of sediments were obtained.

Three areas were selected for study which differed widely in: (A). the size of sediment available for transportation, (B). the amount of sediment supplied to the area, and (C). the physical processes such as waves and currents which sort and transport the sediments. The areas are shown in figure 1, and include a sandy beach and nearshore area at La Jolla, California, which is exposed to the waves from the Pacific Ocean, and two areas along the coast of the Gulf of Mexico. The latter include the barrier island and shallow bay environments near Rockport, Texas, and the shallow shelf and rapidly prograding distributaries of the east Mississippi delta region of Louisiana.

In order to gain an understanding of

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[1] Contribution from the Scripps Institution of Oceanography, New Series No. 786. This investigation was supported by a grant from the American Petroleum Institute, Project 51, and is based in part on research carried out (Inman, 1952; 1953) for the Beach Erosion Board and the Office of Naval Research under contract with the University of California. The writers express their appreciation to F. P. Shepard, Director of Project 51, and to R. S. Arthur, R. L. Miller, M. N. Bramlette, J. D. Frautschy, and P. C. Scruton for their many suggestions and careful reading of the manuscript, to Jean Short and D. M. Poole for assistance in the laboratory analysis of the data, and to J. R. Moriarty for drafting the figures.

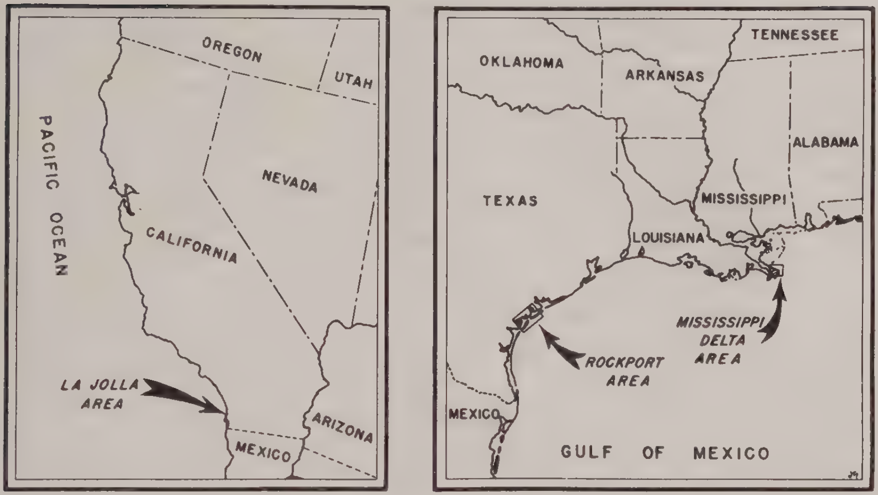

FIG. 1. Location map. Details of the La Jolla, Rockport, and Mississippi Delta areas are shown in figures 4, 7, and 10.

the problem and some of the many variables, it seemed advisable to first study the size distribution pattern of sediments in the La Jolla area where the processes of transportation were somewhat less complicated and the source of material better understood. In this area the principal transporting agents are waves and wave-generated currents and the major source of sediment is sandy material supplied to the area by littoral drift along the coast. Sampling in the La Jolla area was performed on a closely spaced-grid, and was designed to test seasonal as well as environmental variations in the sediments. The results from this study were used as an aid in evaluating the more complex relations found in the Gulf coast environments.

Previous investigation of the relations between the size distribution of sediments and the environment of deposition have been undertaken by many workers. One of the earliest and most rewarding studies of the areal distribution patterns of sediment properties was that by Krumbein and Aberdeen (1937) in Barataria Bay, where they were able to demonstrate that the bottom sediments varied in a systematic manner throughout the lagoon, and that the size distribution of the sediment could in general be related to the environment of deposition. Other investigations of this type include the study of areal variations of beach sands by Krumbein (1938) and Krumbein and Griffith (1938), the sediment studies of Buzzards and Cape Cod Bays by Hough (1940, 1942) and the study of areal and seasonal variations in beach and nearshore sediments by Inman (1953). Parts of this last study are summarized in this report.

METHOD

Because the study was primarily concerned with the character of the surface sediments, the samples were obtained from the upper few centimeters of the sediment with the intent that they be representative of conditions near the water-sediment interface. Beach samples were usually obtained by pressing a glass sample jar into the surface of the sand. This method gave a uniform sample about five centimeters in diameter and four centimeters deep. Offshore sand samples were mostly obtained with a snapper-type bottom sampler (La Fond, Dietz 1948) which penetrates about four centimeters into the bottom. Where only cores were available, which was usually the case in muddy and clayey areas, care was taken to separate and use only the upper few centimeters for this study.

An attempt was made to obtain a sufficient number of samples in each area to delineate the various sedimentary types and to show if the sediments were gradational within the environments. Also, it was intended that the sampling period be of short duration so that the samples would be synoptic, and thus not unduly complicate the study by seasonal variations. However, in the Gulf coast areas, it was necessary to combine two or more seasons' samples into one set of data, and the assumption was made that seasonal variation of particle-size distribution would not unduly complicate the environmental variations. The study in the La Jolla area, which was designed to evaluate seasonal as well as environmental factors, indicated that in general seasonal changes in the sediments were not of significant magnitude to overshadow properties that can be attributed to the location or environment of deposition of the sediment.

Details of the field sampling procedure discussed above, and of the laboratory analysis and synthesis of sediments outlined below are given by Inman (1953).

LABORATORY PROCEDURE

Because this study was primarily concerned with water transported sediments, hydraulic sizes, which are based on settling velocity were used in preference to sizes obtained by sieving. However, in the La Jolla area, both sieve and hydraulic sizes were measured in order to judge the relative merits of the two methods. In general it was found that when the sediment was treated from a hydraulic standpoint it had an increased homogeniety and the areal distribution pattern had improved continuity. The hydraulic diameter is the diameter of a quartz sphere having the same settling velocity as a given particle in distilled water at the same temperature, and more particularly, in this report, its value is understood to be that obtained by the settling methods described below.

The sand-sized fraction of the sediments were anlyzed with the Emery settling tube (Emery, 1938; Poole, et al, 1951) and the finer material by the pipette method (Krumbein and Pettijohn, 1938) or the hydrometer method. Samples that had material both coarser and finer than 1/16 millimeter (4φ) were first wet-sieved on a 1/16 mm sieve, then the coarse and fine fractions were analyzed separately, and the results recombined into one cumulative frequency curve (Inman, 1953). The pipette method was used in the earlier analysis of the fine fractions in the La Jolla area. However, because it is more rapid, a modification of the hydrometer method described by Day (1950) was used for the fine fractions in the Gulf coast areas, after first ascertaining that the method gave results that are comparable to the pipette analysis.

If fine material was present, the sample was defloculated by soaking overnight in a solution of 0.025 normal sodium hexametaphosphate before wet-sieving and final analysis. The settling velocity or hydraulic size determined in this way is not necessarily the depositional size, since the size will depend on the type of clay minerals present and other factors such as chlorinity, pH, etc., at the time of deposition. For this reason no attempt was made to subdivide sediments containing more than about 45 percent clay into separate classes; the clayey sediments are all classed as type IV.

MEASURES OF SIZE DISTRIBUTION

The phi notation of Krumbein (1936), where φ equals minus the logarithm to the base two of the particle diameter in millimeters, is used as a size scale in this

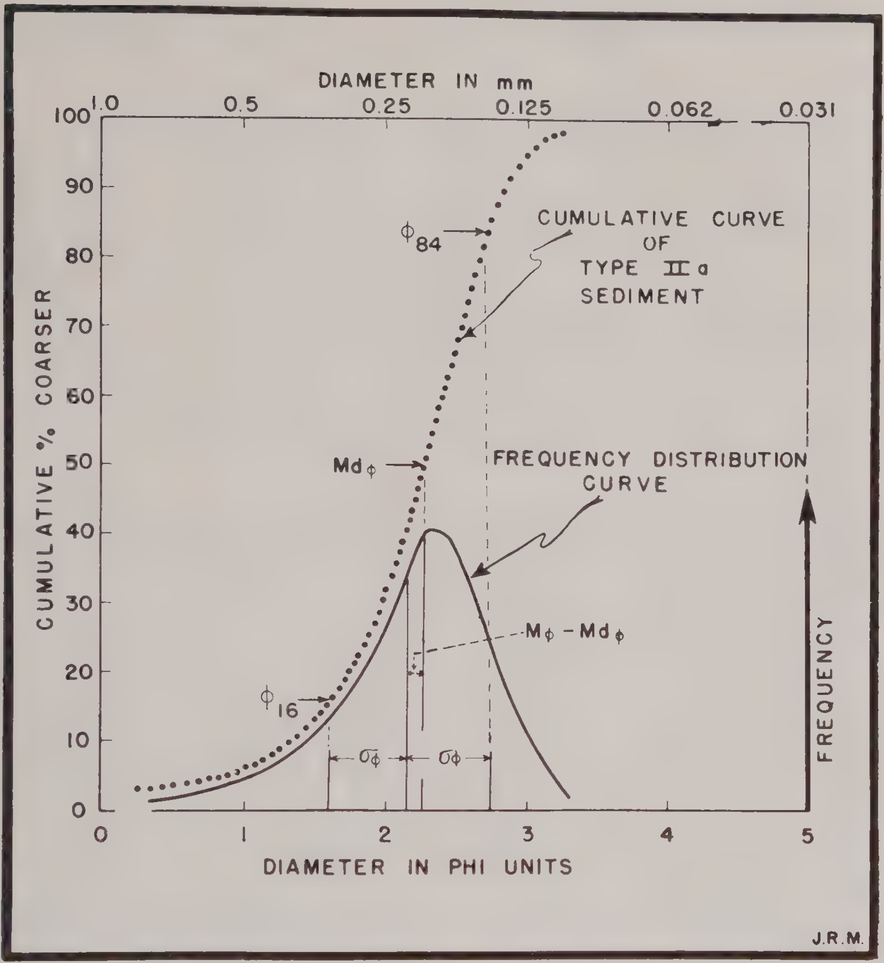

FIG. 2. Graphic illustration of the phi size distribution measures for a Type IIa sediment from the surf zone at La Jolla, California. Note that the median diameter, Md_ϕ, is a fair approximation to the modal diameter, while the phi mean diameter, $M_\phi = \frac{1}{2}(\phi_{16} - \phi_{84})$, is displaced more towards the coarser particle sizes. The phi deviation measure, $\sigma_\phi = \frac{1}{2}(\phi_{84} - \phi_{16})$, is a measure of spread or sorting, and the phi skewness measure, $\alpha_\phi = \frac{M_\phi - Md_\phi}{\alpha_\phi}$, indicates the degree of symmetry of the frequency distribution curve. Values for these measures are given in Table 2.

paper because a logarithmic diameter is more convenient in depicting the statistical relations of sediments. In the phi notation, values of 0, 1, 2, 3, 4, etc., correspond to particle diameters in millimeters of 1, ½, ¼, ⅛, 1/16, etc., respectively.

In general, the first three moment

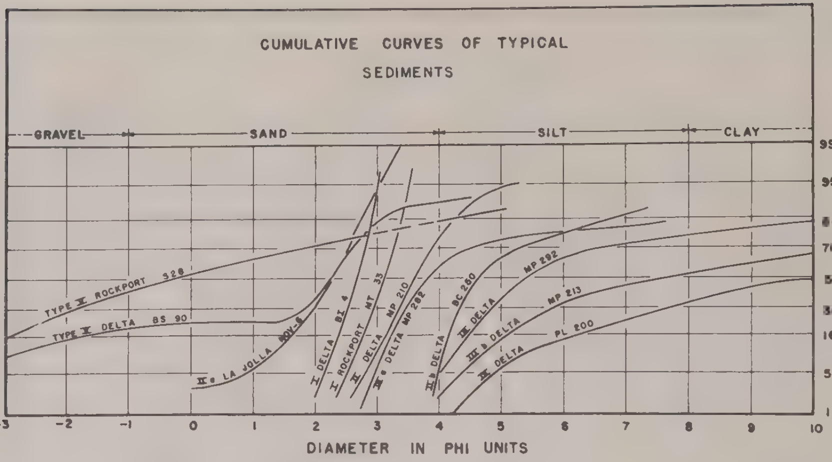

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FIG. 3. Cumulative curves of typical nearshore sediments. Frequency distribution curves for these samples are shown in figures 5, 8, and 11, and the values of the phi size distribution measures are listed in Table 2.

measures of a simple frequency distribution curve give the essential features of the distribution. However, the dependence of moment measures on the entire distribution limits their practical application to sediments, since size analysis frequently results in open-ended curves which do not give the coarse and fine limits of the distribution. Also, moment measures become tedious where numerous samples are involved. For these reasons the particle-size distributions of the sediments were expressed in terms of phi measures (Inman, 1952) that serve as approximate graphic analogies to the moment measures commonly employed in statistics. The parameters used include the median diameter, a measure of standard deviation, and a measure of skewness. They are computed from three percentile diameters obtained from the cumulative size-frequency curve of the sediment and are defined as follows:

1) the phi median diameter $Md_\phi = \phi_{50}$
2) the phi deviation measure $\sigma_\phi = \frac{1}{2}(\phi_{84} - \phi_{16})$
3) the phi skewness measure $$\alpha_\phi = \frac{M_\phi - Md_\phi}{\alpha_\phi}$$

Where $M_\phi = \frac{1}{2}(\phi_{16} + \phi_{84})$ is the phi mean diameter, and ϕ_{16}, ϕ_{50}, and ϕ_{84} are the diameters in phi units corresponding to the 16th, 50th and 84th percentiles respectively of the cumulative weight-percent (coarser) curve. Cumulative curves of typical sediment samples are shown in figures 2 and 3.

As an aid in the visual interpretation of the size distribution measures, the frequency distribution curves of typical sediments were obtained by differentiating the cumulative frequency curves. This was done by the graphic method described in Krumbein and Pettijohn (1938), and a typical curve from the La Jolla area is shown in figure 2.

The phi median diameter, Md_ϕ, is a measure of central tendency. It was used in preference to the mean, M_ϕ, because: (A) it is obtained directly from the cumulative curve without interpolation, (B) it is less influenced by extreme values of skewness, and (C) it usually serves as a good approximation to the principal modal diameter (fig. 2). The mode, which may be the more significant measure for many sediment studies, was not used because it is very difficult to obtain. The phi deviation measure, σ_ϕ, is a measure of sorting or spread and is approximately equal to the standard deviation of statistics. Since one phi unit is equivalent to one Wentworth division, the phi deviation measure gives the standard deviation of the curve in terms of Wentworth units.

In a symmetrical distribution the mean, median and the mode coincide, but if the distribution is skewed they depart from each other. The extent of the departure between the mean and the median is used as a measure of skewness. The phi skewness, α_ϕ, gives the departure of the mean from the median in terms of the phi deviation measure, and is therefore a dimensionless measure of skewness, independent of the spread or sorting of the distribution.

The phi skewness measure is zero for a symmetrical size distribution. If the distribution is skewed towards smaller phi values (coarser diameters), the phi mean is numerically less than the median and the skewness is negative as in figure 2. Conversely, α_ϕ is positive for a distribution skewed towards higher phi values. This measure of skewness is related to the moment skewness, α_3, of statistics by the approximate relationship, $\alpha_3 \simeq 6\alpha_\phi$. Comparisons of phi measures and moment measures for two of the samples illustrated in figure 5 (Nov.-34, May-60) are given in Inman (1952).

SIZE DISTRIBUTION DIAGRAMS

Experience has shown that the measures of sediment size distribution are somewhat interdependent, and that a physical relationship exists between the median diameter and the deviation and skewness measures for most water transported sediments (Inman, 1949, and Griffiths, 1951). In general, sediments with median diameters within the Wentworth range of fine sand tend to be better sorted and more symmetrical than coarser or fine material regardless of the environment of deposition. For this reason it is advantageous in studying the particle-size distribution of a large number of samples to plot them in such a manner that both the variation and the interdependence of the size parameters can be shown. To accomplish this the descriptive measures of the bottom sediments were plotted on a size distribution diagram in which the phi deviation and skewness measures are plotted against the median diameter. Diagrams of this type were constructed for each area, and are shown in figures 5, 8, and 11.

It is sometimes convenient to visualize the median, deviation, and skewness in the size distribution diagram as the x, y, and z axes of a Cartesian coördinate system in space. In this sense the pattern of plotted points delineate solids in space, and the number of plots per unit volume indicate the density of the solid. If different symbols are used to represent the different environments of deposition, as in figure 5, the density of plot of a given symbol is a measure of the degree of similarity of the size distribution of sediments from that particular environment. As an aid in interpreting these population densities and their differences, all of the samples in each sediment type were analyzed and described mathematically. The analyses included the mean value, standard deviation and correlation coefficients for each of the three size distribution measures in each sediment type. In the interest of brevity, the details of this phase of the investigation are not included in this report. A statistical treatment of the sediment types in the La Jolla area, using multivariate analysis as a tool, is given by Miller (1954).

In general it was found that the sediments could be divided into types on a basis of their grouping on the size distribution diagrams, and that these types were characteristic of the environments of deposition. The areal distribution of the sediment types determined from the size distribution diagrams are shown in figures 6, 9, and 12. A list of all sediment types and the number of samples from each area are given in Table 1, and a tabulation of the phi size distribution measures for typical sediments illustrated in the various figures is given in Table 2.

LA JOLLA AREA

A beach and sandy shelf environment along the Pacific coast of the United States was selected for the first and most detailed investigation. The area is situated just north of La Jolla, California, where Point La Jolla forms a small hooked bay which is exposed to the waves from the Pacific Ocean (fig. 4). The shelf area within the bay is cut by two main branches of a submarine canyon, which extend across the shelf to within about 700 feet of the shoreline, and separate the area from the adjacent shelves to the north and south. A beach of fine sand extends for a mile along the shore between the two canyon heads. This section is called Scripps Beach and is terminated by rocky areas just south of each canyon head.

TABLE 1.—*Number of sediments analyzed for each area and plotted in figures 5, 8, and 11*

Sediment Type	La Jolla Area	Rockport, Texas Area	Mississippi Delta Area
I Beach sands	58	107	26
IIa Surf zone sands	135	**	**
II Offshore and shelf sands	183	50	61
IIb Delta silts	—	—	16
IIIa Transition sands	27	115	27
III "Muds"	—	94	35
IIIb Fine "muds"	—	42	31
IV Silty clays	—	115	35
V Shell sand and reef detritus	—	18	8
	403*	541	239

* In addition to these samples from Scripps Beach and intercanyon shelf, 239 samples were analyzed from areas to the north and south (Inman, 1953).

** Type IIa sands probably exist in the Rockport and Mississippi Delta areas but were not sampled.

TABLE 2.—*Phi size distribution measures for typical sediments illustrated in figures 2, 3, 5, 8, and 11.*

Area	Sediment Type	Sample No.	Phi Median Diameter, Md_ϕ	Phi Deviation Measure, σ_ϕ	Phi Skewness Measure, α_ϕ
La Jolla	I	Mar.-11	2.41	0.25	−0.04
	IIa	Nov.-6	2.27	0.58	−0.22
	II	May-60*	3.28	0.41	−0.10
	IIIa	Nov.-34*	3.78	0.74	+0.38
Rockport, Texas	I	MT-33	3.12	0.29	−0.12
	II	J-37A	3.72	0.50	+0.32
	IIIa	S-240B	3.67	3.63	+0.84
	III	J-22A	4.70	3.30	+0.72
	IV	S-115A	9.75	Insufficient Data	Insufficient Data
	V	S-28A	1.17	5.49	+0.14
	IIIa	Residue of S-28A**	3.55	4.27	+0.80
East Mississippi Delta	I	BI-LT-4	2.67	0.27	−0.10
	II	MP-210	3.57	0.48	+0.05
	IIb	BC-250	4.56	1.24	+0.63
	IIIa	MP-282	3.47	3.70	+0.80
	III	MP-292	5.37	2.75	+0.67
	IIIb	MP-213	7.57	4.27	+0.40
	IV	PL-200	9.92	Insufficient Data	Insufficient Data
	V	BS-90	2.22	2.49	−0.70

* Comparisons of phi measures and moment measures for these samples are given by Inman (1952).

** Residue of Type V (S-28A) sediment, after the carbonates had been removed by treating the sample with dilute HCl, has a Type IIIa distribution similar to the adjacent sediments east of Panther Reef in San Antonio Bay (see figures 7 and 8).

It is thought that the major source of sand for the beaches to the north of La Jolla is from streams and cliff erosion, and that in general this material has a net drift to the south in response to the direction of wave approach. There is a tendency for the size of the beach material to decrease towards the south, and the finest sand along this section of coast is found on Scripps Beach.

Scripps and La Jolla submarine canyons form a natural sediment barrier so that any sand-size material supplied to the intercanyon shelf and beach area must enter the area shoreward of the precipitous canyon heads. Since the erosion of cliffs along Scripps Beach does not provide a significant quantity of sand and the net drift of sand is to the south

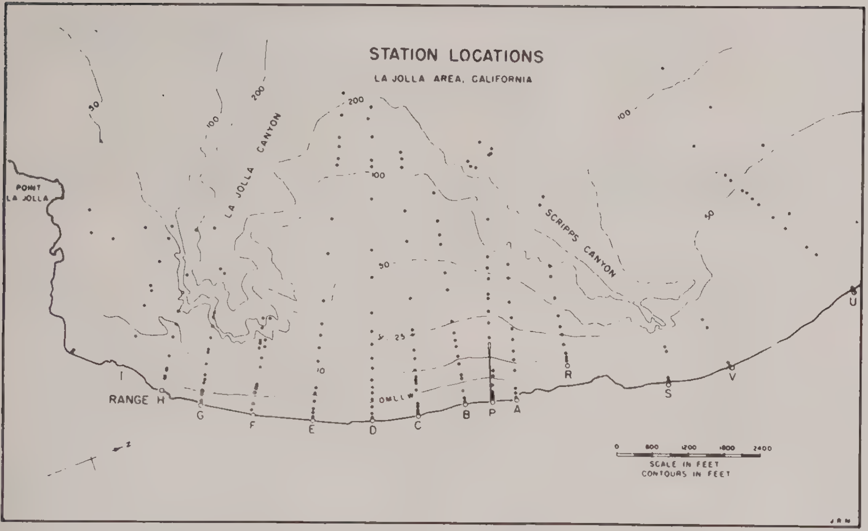

FIG. 4. Location of sediment samples in the area near La Jolla, California. Five series of samples were obtained at most of these stations.

(Inman, 1953), the major source of sediment must be from the north and must enter the area across a narrow 700-foot zone along range S at the head of Scripps Canyon (fig. 4).

The investigation in the La Jolla area was designed to test seasonal as well as environmental variations in sediment distribution. Five series of sediment samples were collected from Scripps Beach and the adjacent intercanyon shelf at intervals of approximately 2½ months from the summer of 1949 to the summer of 1950. Each series consisted of an average of 86 samples from an area of approximately one-half square mile on the beach and inter-canyon shelf along ranges A through H, P, and R, with an average of 20 additional samples from ranges I, S, U, and V situated to either side and at the heads of the canyons.

Concurrent with the sediment sampling and on the same grid, five detailed topographic surveys to determine the changes in sand level resulting from seasonal changes in waves and currents were made. The results of the sand level surveys are described in Shepard and Inman (1951), and a comprehensive discussion of the sediment study is given in Inman (1953).

On a basis of the grouping of the size distribution characteristics of the sediment (fig. 5) and the areal distribution (fig. 6), the sediments on Scripps Beach and inter-canyon shelf are grouped into three general types. Type I consists of beach foreshore sands, which are the best sorted sediments in the LaJolla area. Sands from the surf zone are designated as Type IIa, and are characteristically coarser and more poorly sorted (higher α_ϕ values) than adjacent sediments inshore or offshore. These grade into Type II which are found on the relatively flat portions of the shelf from the surf zone out to depths of approximately 100 feet, and are therefore the most abundant sediment on the inter-canyon shelf. Type II sediments are predominantly well sorted, very fine sands, with less than about three percent silt. Seaward of the Type II sediments in areas where there is sloping bottom, the silt content usually

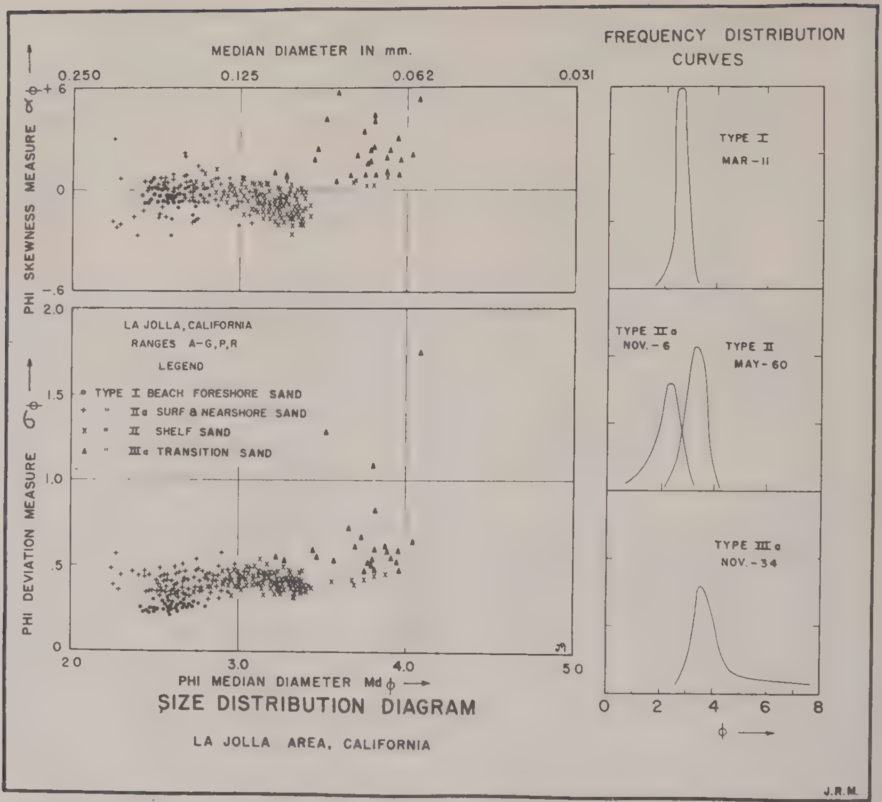

FIG. 5. Diagram showing the size distribution of sediments in the La Jolla area. Frequency distribution curves of typical samples are drawn to the right of the diagram, and the areal distribution of sediment types is shown in figure 6. This size distribution diagram is a compilation of data from five surveys taken at intervals of approximately two months; the density of plot indicates that seasonal variations are not great. Individual diagrams for each survey are given in Inman (1953).

increases, the sediment characteristically has a positive skewness, and is more poorly sorted. These sediments are classed as Type IIIa, and while usually occurring in deeper water, they are also found in shallow water near the submarine canyon heads. Because, in the La Jolla area, they occur only where the bottom slopes are greater than about 1:15, it is thought that sloping bottom is an important environmental factor and they are referred to as "slope" or transitional sediments. The reduction in wave action over the sloping bottom apparently allows fine sediments to accumulate along with the sand sized material from further up slope. Also, the presence of a slope helps to reduce the sorting effect of the wave motion. In a sense this is a transition zone where fine material settles out because of reduced wave intensity, and sand size material is introduced by gravity movement down slope. Type IIIa sediments are discussed in more detail in the section on the Rockport, Texas area.

Sediments from the stations on the beach and shelf north of Scripps were similar to those on the inter-canyon shelf except that the northern beach sands were slightly coarser and the shelf sediment (Inman, 1953) somewhat finer than their counterpart from the inter-canyon shelf. The difference in shelf sediments can be accounted for by Scripps submarine canyon which prevents the transportation of sediments in deep water from one shelf to the next except as suspended load. Therefore the main source of inter-canyon sediment is sand size material transported across the shallow shelf at the head of the canyon.

The sediments on the rocky shelf around Point La Jolla differ markedly from those of the inter-canyon shelf. The Point La Jolla sediments occur in patches separated by many low rock outcrops and ridges. These sediments are coarser, somewhat more rounded, have more shell fragments, are frequently bi-modal, and in general do not grade from one type to another as do the shelf sediments to the north. The transition between the Point La Jolla shelf sediments and the fine sands to the north occurs near the head of La Jolla canyon and results in a confused sediment distribution along H range. These sediments are classed as Type V, and resemble Type V sediments from the Gulf coast areas in that they are bi-modal, although they generally are somewhat beter sorted and have a lower shell content than their counterpart from the Gulf areas.

ROCKPORT, TEXAS, AREA

Both of the Gulf coastal areas are larger than the La Jolla area and present a much more complex and less well understood situation in so far as sediments and processes of transportation are concerned (Shepard and Moore, 1955; Scruton, 1955).

The region around Rockport, Texas, consists of a series of shallow bays and lagoons separated from the flat continental shelf by long barrier islands (fig. 7). The coastal plain rivers which trans-

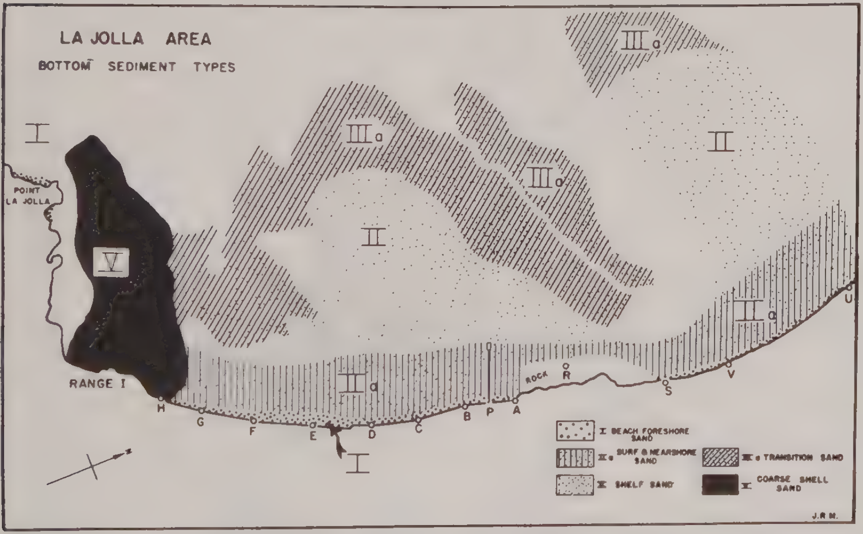

FIG. 6.—Areal distribution of bottom sediment types in the La Jolla area. Types are defined in figure 5, and the topography and location of samples are shown in figure 4.

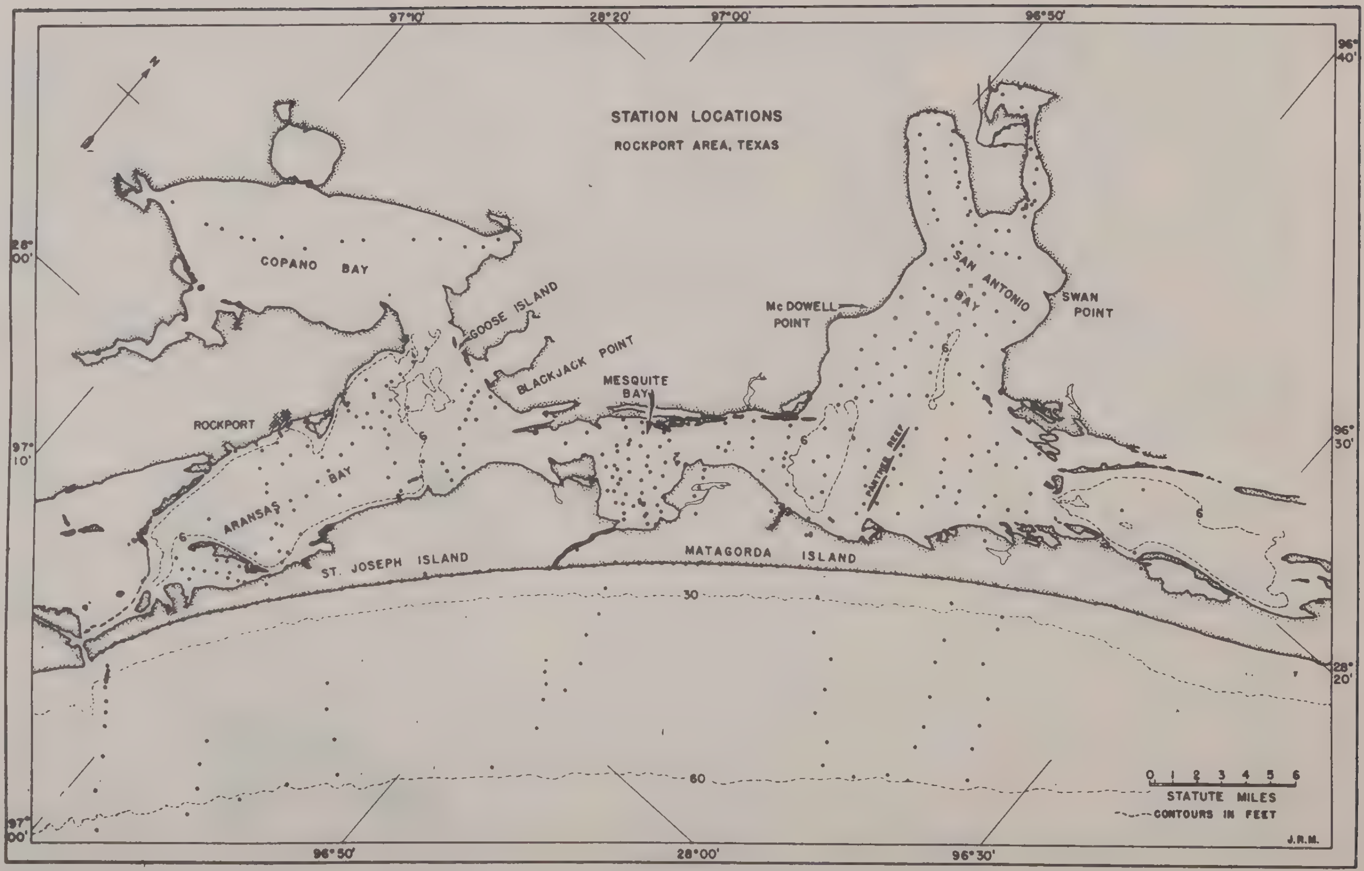
STATION LOCATIONS
ROCKPORT AREA, TEXAS
N
COPANO BAY
GOOSE ISLAND
BLACKJACK POINT
MESQUITE BAY
McDOWELL POINT
SAN ANTONIO BAY
SWAN POINT
PANTHER REEF
ROCKPORT
ARANSAS BAY
ST. JOSEPH ISLAND
MATAGORDA ISLAND
6
30
60
97°10'
28°20'
97°00'
96°50'
96°40'
28°00'
97°10'
96°30'
28°20'
97°00'
96°50'
28°00'
96°30'
0 1 2 3 4 5 6
STATUTE MILES
CONTOURS IN FEET
J.R.M.

FIG. 7. Location of sediment samples in the Rockport, Texas area.

port predominantly clay size material are the main source of sediment for the upper bays. The coarser sand size sediment in the lower bays and on the islands and barrier beaches is apparently supplied by longshore drift from the northeast. This material is introduced to the bays through various passes and inlets, and is carried across the barrier islands by winds and storm waves. Material coarser than about one-half mm is essentially all shell debris which is derived largely from the numerous oyster reefs in the bays.

Within the bays, sediment is transported principally by wind-induced currents, flow from the rivers, and tidal currents. The sediment distribution is also influenced by local wind waves, which in the shallow bays, where the water is generally less than six feet deep, are effective in stirring and transporting sediments. In addition, benthonic organisms are apparently effective in reworking and disturbing bottom sediments.

Five sediment types and two sub-types were established in the Rockport area on a basis of the tendency of environmentally similar points to cluster (fig. 8). The areal distribution of types is shown in figure 9. As in the La Jolla area samples from the beach foreshore are the best sorted sediments in the area and are classed as Type I. These sediments have a median diameter ranging from about 2.9ø to 3.5ø, a sorting in terms of the phi deviation measure, σ_ϕ, of 0.25 to 0.35, and zero to slight negative skewness. These sediments occur on the beach foreshore along the seaward side of the barrier islands, and along portions of the bay shores that are exposed to wind waves as at Goose Island and Blackjack Point in Aransas Bay, and Swan Point and McDowell Point in upper San Antonio Bay. Type I grades offshore in the Gulf of Mexico into somewhat more poorly sorted sands which are classed as Type II sediments. Type II sands are also found in the bays, usually in small areas close to shore as at Goose Island and Blackjack Point.

The fine sediments with median diameters in the silt and clay sizes are grouped in three classes grading from Type III, which are the coarser, to Type IIIb; with medians in the fine and very fine silt sizes, to Type IV, which includes all sediments containing more than 50 percent clay.

The silty clays, Type IV, are the most abundant bay sediment and are found in deeper water in the central portions of the bays. Type IV sediments grade shoreward into the coarser Type IIIb (fine "mud")[2] and III ("mud"), although the intermediate Type IIIb occurs in such limited areas that it is generally not included in the areal distribution diagram (fig. 9). Type III sediments are found in the bays, but are most abundant in the Gulf where they border the nearshore sands of Type II.

The cuspate pattern of the Type II and III sediments offshore from the barrier islands appears to be real, although it is not based on a large number of samples (figs. 7, 9). This pattern may be related to the position of present and past inlets through the barrier islands or it may result from some more recondite process such as local intensification of energy associated with long period waves or surges generated by the alteration of groups of high and low waves in the surf zone. In this connection, Munk (1949) concluded that the surf zone acts as a radiating line source which returns approximately one percent of the incoming wave energy in the form of two to four minute period waves which he termed "surf beat." Williams and Isaacs (1952) and Isaacs, et al (1951) describe processes by which the seaward moving surf beat wave may be refracted and reflected, thus resulting in offshore regions

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[2] The word "mud" is used here and in figures 9 and 12 only in a general way to give the reader a term descriptive of the Type III and IIIb sediments which are defined in a more precise manner in figures 8 and 11.

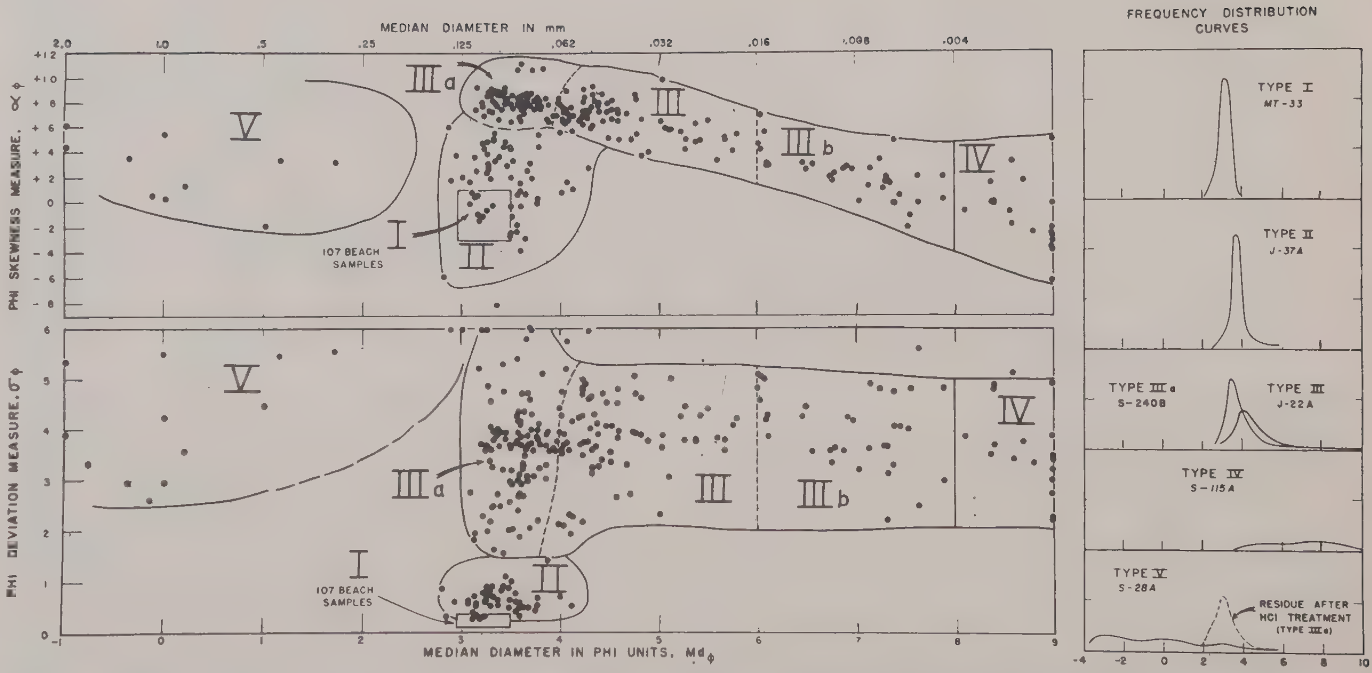

FIG. 8.—Size distribution diagram of sediments in the Rockport, Texas area. Frequency distribution curves of typical samples are drawn to the right of the diagram. The Type IIIa curve (dashed line) shown with the Type V curve is for the residue of sample S-28A after the carbonates were removed, and indicates that the size distribution characteristics of the Type V sediments result principally from shell fragments.

of wave convergence and reinforcement.

There is a pronounced change in the character of the sediment size distribution from sediments that are predominantly sand to those which are predominantly silt or clay. Within the sand sizes, sediments of Type I grade into Type II, and as mentioned above, within the silt and clay sizes there is a gradation from Type III, to IIIb to IV. However, in the bays where sands border finer sediments a distinctly different size distribution results which is in marked contrast with the clean sands of Type II. This material is classed as Type IIIa and is similar to Type II in range of median diameters, but differs in that it has poor sorting and a pronounced positive skewness (figs. 3, 8).

Type IIIa sediments apparently represent a transition between coarse and fine sediments, and occur when sand size material is mixed or deposited with an abundance of fine material in the presence of a weak or only partially effective sorting agent. This type probably results from the basic differences between the modes of transport of sand size material on the one hand and silt and clay on the other (Inman, 1949). Sand, due to a relatively high settling velocity, is transported principallv as bed load. Because of the size of the particles, a sand bottom is usually hydrodynamically rough, so that relatively weak currents result in sufficient bottom stress to move particles and to form ripples. Sediments in which silts and clays predominate are less easily moved on the bottom, but once placed in suspension are easily carried by weak currents. Therefore, if sandy material is present, and the transporting agent is rigorous as in the case of wave motion near the breaker zone, the fine material will be retained in suspension until it reaches quiet water, where it can be deposited. As mentioned previously the clays are found in the deeper portions of the bays where wave action is less pronounced. The transition type sediment, IIIa, is most common in Mesquite Bay and the southeastern portion of San Antonio Bay where sandy material is supplied through the inlets and by wind and overwash from the barrier islands, and mixes with clayey material from the rivers. These areas are shallow so that the small wind waves generated in the bays result in the movement of bottom material, but are not of sufficient intensity to prevent deposition of some clay. It is also probable that burrowing organisms aid in mixing these sediments and thus prevent clayey material from completely burying the sand size material during quiescent periods.

Detrital material from the oyster reefs in the bay provides an additional source of sediment which is somewhat coarser than other material supplied to the area. The influence of this material is usually limited to the reefs and the areas immediately sourounding them. Because of the size of this material, its combination with other bay sediments results in a distribution which is very poorly sorted, and often bi-modal. These sediments are classed as Type V. When the shell material is removed from a sample of this sediment, the residue usually has a distribution similar to that of the sediments in the area adjacent to the reef. The frequency distribution curve for a Type V sediment from Panther Reef in the south central portion of San Antonio Bay is shown in the inset on figure 8, together with the distribution of the residue after the carbonates had been removed by treating the sample with dilute hydrochloric acid. In this case the residue had a Type IIIa distribution as did the sediment just to the east of the reef. The size distribution measures for the total sample and the residue are listed in Table 2.

EAST MISSISSIPPI DELTA AREA

The area studied covers approximately 450 square miles and includes the rapidly prograding distributaries of the east

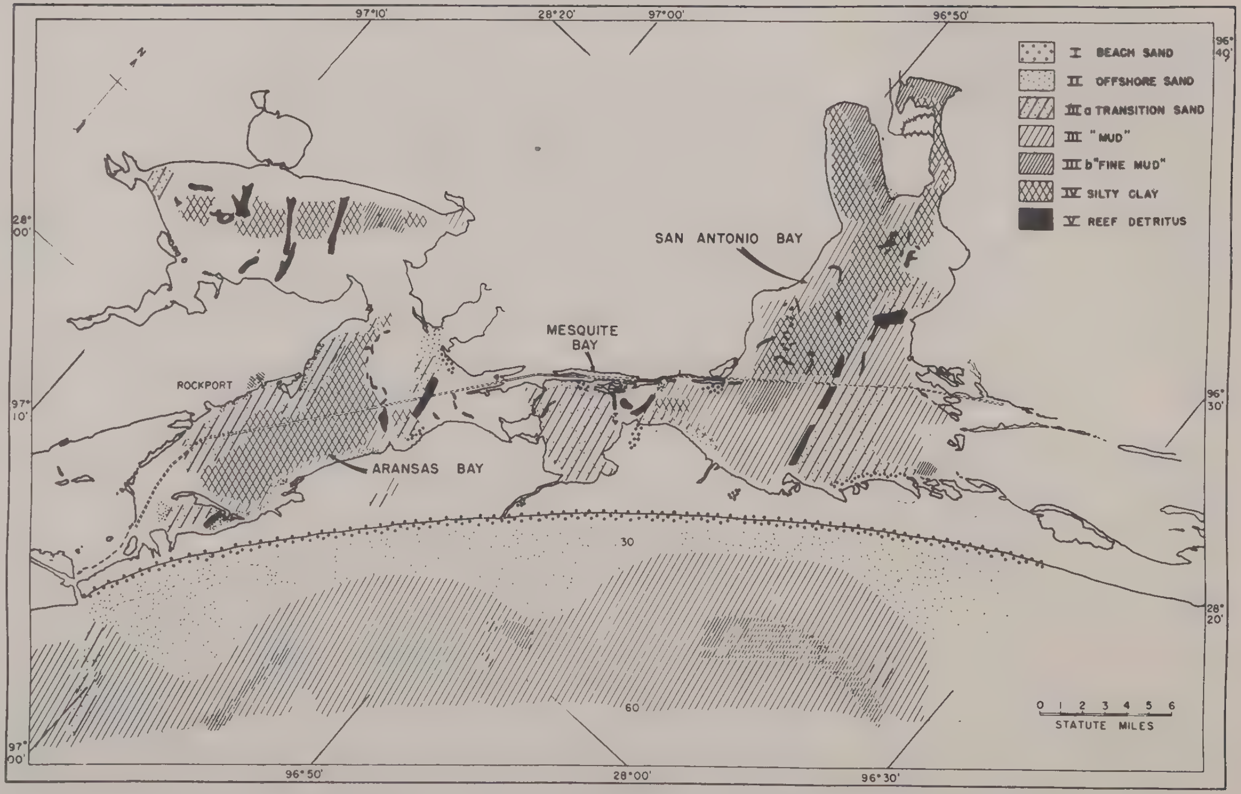
97°10'
28°20'
97°00'
96°50'
96° 40'
28° 00'
97° 10'
96° 30'
28° 20'
97° 00'
96°50'
28°00'
96°30'
N
I BEACH SAND
II OFFSHORE SAND
III a TRANSITION SAND
III "MUD"
III b "FINE MUD"
IV SILTY CLAY
V REEF DETRITUS
SAN ANTONIO BAY
MESQUITE BAY
ROCKPORT
ARANSAS BAY
30
60
0 1 2 3 4 5 6
STATUTE MILES

Fig. 9.—Areal distribution of bottom sediment types in the Rockport, Texas area. Types are defined in figure 8, and sample locations are shown in figure 7.

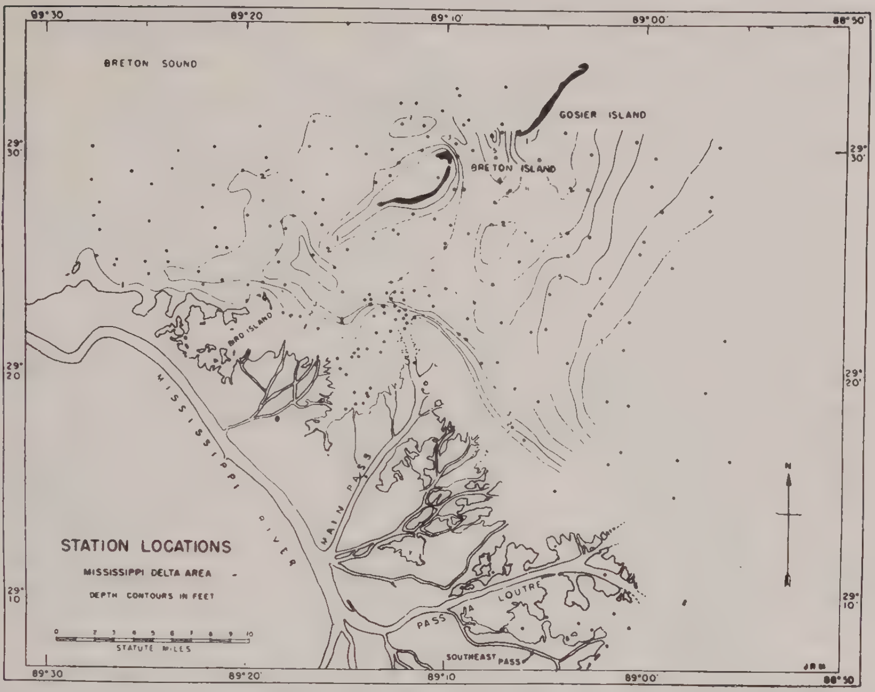
BRETON SOUND
GOSIER ISLAND
BRETON ISLAND
BRD ISLAND
MISSISSIPPI RIVER
MAIN PASS
LOUTRE
PASS
SOUTHEAST PASS
STATION LOCATIONS
MISSISSIPPI DELTA AREA
DEPTH CONTOURS IN FEET
STATUTE MILES
N
89°30
89°20
89°10
89°00
88°50
29° 30
29° 20
29° 10

FIG. 10. Location of sediment samples in the east Mississippi Delta area of Louisiana.

Mississippi delta and the surrounding shallow shelf, portions of Breton Sound, and the sandy areas around Breton Island (fig. 10). This area is complex, both as regard to sources and quantity of sediment supplied to it, and as regards the processes such as river flow, wave action, and tides that transport and deposit the sediments (Scruton, 1955).

There are two major sources of sediment for the area. The principal source is the Mississippi River which supplies large amounts of silt and clay and some fine sand. Deposition of this material has resulted in a rapid growth of the delta, especially in the vicinity of Main Pass during recent years. The second source, which is predominantly sandy material, is supplied from the Chandeleur chain of islands just to the north of Main Pass. This sandy material is carried south by longshore drift and has resulted in the formation of Gosier and Breton Islands and the large shallow area of sand to the east of Breton Island. Also, minor amounts of material are supplied by reworking of older deposits and by shell forming organisms.

The best sorted and coarsest sand was found on Breton Island. This material is designated as Type I, and is represented by 26 samples from the beach foreshore along the southern portion of the island, and from a traverse across the western end of the island (figs. 11, 12). In addition to the island sands, there are some areas associated with the present sedimentary cycle of the Mississippi River where wave action has been sufficient to sort the river-borne material and form sand beaches despite the predominance of fine sediments in the region.

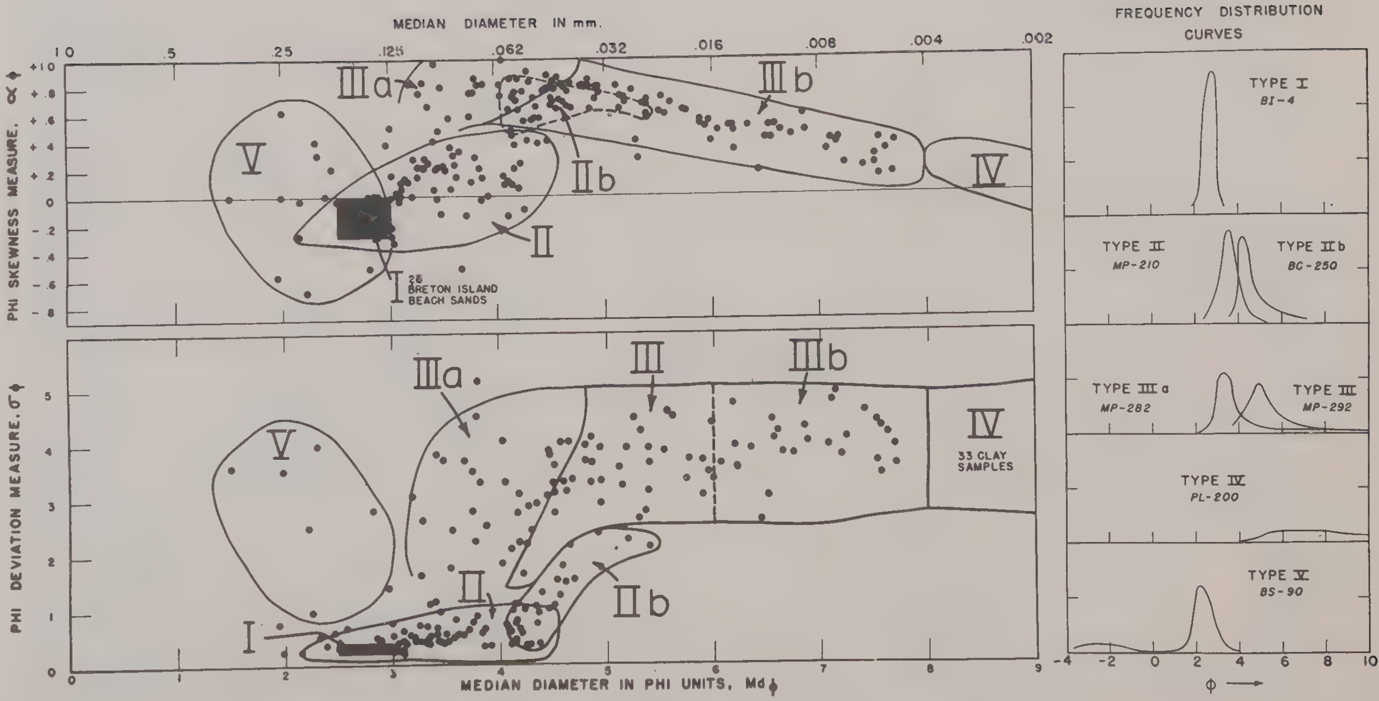

FIG. 11. Size distribution diagram of sediments in the east Mississippi Delta area with frequency distribution curves of typical sediments.

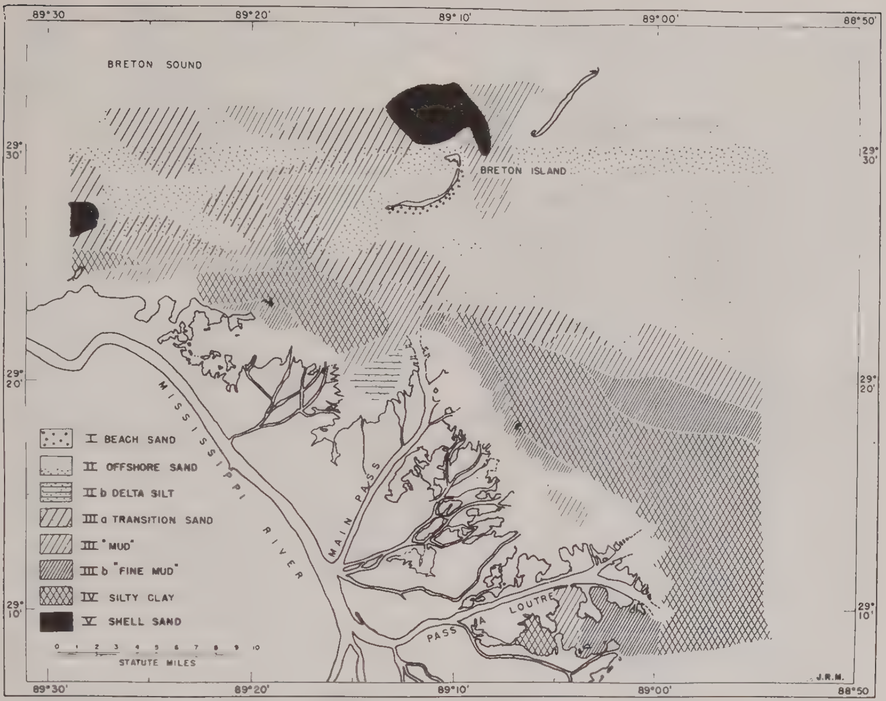
89°30'
89°20'
89°10'
89°00'
88°50'
29° 30'
29° 20'
29° 10'
BRETON SOUND
BRETON ISLAND
MISSISSIPPI RIVER
MAIN PASS
PASS A LOUTRE
I BEACH SAND
II OFFSHORE SAND
II b DELTA SILT
III a TRANSITION SAND
III "MUD"
III b "FINE MUD"
IV SILTY CLAY
V SHELL SAND
0 1 2 3 4 5 6 7 8 9 10
STATUTE MILES
J.R.M.

FIG. 12. Areal distribution of sediment types in the east Mississippi Delta area. Types are defined in figure 11.

Such an area exists along the outer portion of Southeast Pass, and while not sampled during this study, probably includes Type I sediments.

Type II sediments are somewhat finer and more poorly sorted than the beach sand, but have median diameters of sand size. These sediments are found mostly in the areas around Breton and Gosier Islands, particularly to the east and south, and are the most abundant sediment type, representing about 25 percent of the surface samples in the Delta area. As indicated previously these sediments are quite different from the present Mississippi River sediments, and are probably derived from the Chandeleur Islands to the north and east.

Where this large body of offshore sand is bordered by "muds" (Type III), a transition sediment designated as Type IIIa is found. This transition sediment is characterized by a median diameter around 4_ϕ, very poor sorting, and a high positive skewness (fig. 11). It is thought that this type of sediment distribution results from the mixing of river-borne muds with offshore sands much in the same manner as discussed above for the bay sediments in the Rockport, Texas area. Since this sediment type is quite different from the others in the area, it may prove useful in determining the areal extent of effective deltaic deposition in the direction of sand bodies.

Towards the delta, Type IIIa sediments grade into Type III, a "mud" derived from the river and found predominantly in shallow water along the delta front. The finer portion of Type III, that is, sediments with median diameters between 6_ϕ and 8_ϕ, have arbitrarily been classed as Type IIIb. This type is a gradation between Type III and the silty clays of Type IV. The silty clays are found in the area offshore from Pass a Loutre, and as in the Rockport area, are deposited in the deeper quiet water.

A relatively well-sorted silt was found in some samples from the shallow distributaries and marshes on the delta. This material plots (fig. 11) between the sands of Type II and the "muds" of Type III and has been designated as Type IIb. The areal distribution of Type IIb is not well delineated, but it is thought that this type results from fractionation of the material supplied to the area by the river. Apparently sand sized material is retained in the deeper channels where it is transported as bed load, and clay size material is retained in suspension and carried to deeper water beyond the delta front; leaving the silt size fraction of the river load to be deposited off the smaller distributaries and in the marshes.

After the size distribution characteristics of the sediments from the east Mississippi delta area had been determined by means of the size distribution diagram (fig. 11), they were replotted, for purposes of comparison on a conventional triangular diagram (fig. 13) in which the end members of the triangle represent the percentages of sand, silt, and clay in the sample. This method of representing size distributions has many useful applications, but for these sediments does not show the differences between sediment types as clearly as a size distribution diagram of the kind shown in figure 11. This is because the triangular diagram is based on the middle and two end members of a continuous scale. Thus, even when the sediment contains all three constituents, sand, silt, and clay, the triangular diagram can furnish no more information about size distribution than a histogram with three classes. For this reason the triangular diagram is quite effective in displaying differences between sediments that differ markedly in particle-size, but is relatively ineffective for sediments that fall within the same range of sizes and differ principally in degree of sorting or skewness.

SUMMARY AND CONCLUSIONS

The purpose of the investigation was to study the particle-size distributions of surface sediments in various nearshore environments and to determine the pattern of sediment properties resulting from different transporting processes and from different amounts and types of sediment supply. Basically the problem involves the treatment of numerous populations to ascertain their relationship to one another and to the various environments of deposition. It should be emphasized that the plots shown in figures 5, 8, and 11 represent samples from natural populations, and that in this paper, inference about the populations

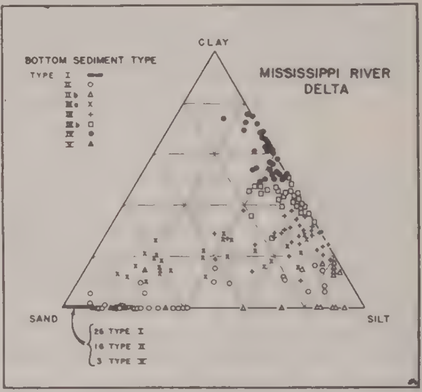

FIG. 13. Distribution of east Mississippi Delta sediments illustrated on conventional triangular diagram in which the end members of the triangle represent the percentage of sand, silt, and clay. The sediment types were determined on the size distribution diagram in figure 8. The triangular diagram is effective in differentiating between sediments that differ mainly in particle size (Types IIIb and IV), but is relatively ineffective for sediments that fall within the same range of sizes and differ principally in degree of sorting or skewness (Types, I, II, IIIa, and V).

has been drawn by inspection from the samples. The examples which have been selected for illustration are typical of their type, but should not be construed as being diagnostic in themselves. Rather, it is the distribution or pattern of the populations as a whole which are significant, and which if properly interpreted may aid in defining the size distribution characteristics of certain kinds of deposits.

The particle-size distribution of the surface sediments from the three areas were described in terms of the median diameter and a measure of sorting (deviation) and skewness. These measures were considered as tri-variate functions and plotted on size distribution diagrams, and the character of the sediments in a given environment determined by the grouping and density of points on the diagrams (figs. 5, 8, 11). In general this method facilitated the delineation of sediment types on a basis of their particle-size distribution, and it was found that these types were characteristic of the environments of deposition. The areal distribution of the various sediment type are shown in figures 6, 9, and 12. Comparison of the size distribution diagrams and the areal distribution of sediment types indicates that in some instances there is a high degree of similarity in the size distribution of sediments within a given environment and between similar environments in different areas.

The sediments were divided into five major types. Sediments that were relatively well sorted and had median diameters in the sand sizes were classed as Types I and II. More poorly sorted material, with medians principally in the silt and clay sizes were classed as Types III and IV, and relatively coarse sediments derived chiefly from shell fragments and reef detritus were classed as Type V. Type I sediments consisted predominantly of beach sands which were the best sorted sediments in all areas. As a rule Type I sediments graded offshore into somewhat more poorly sorted sands which were classed as Type II. The finer sediments of Type III and IV were also gradational within their types and were usually found in relatively quiet water. The Type V sediments, because of the relatively coarse size of the shell fragments and reef detritus which characterized them, were usually poorly sorted and often bi-modal. They were limited in extent, and their occurrence illustrates the importance of local conditions in producing special effects. This indicates that caution must be used in extrapolating findings from one area to another.

There was a pronounced change in the character of the sediment size distribution from sediments that were predominantly sand to those which were predominantly silt or clay. Where sands border finer sediments a distinctly different size distribution, classed as Type IIIa, was found. This material was similar to the Type II sands in median diameter, but differed in that it had poor sorting and a pronounced positive skewness. These sediments apparently represent a transition between coarse and fine sediments, and occur when sand size material is mixed or deposited with fine material in the presence of a weak or only partially effective sorting agent. Its skewed size distribution probably results from the basic differences between the mode of transport of sand size material as bed load and the tendency for silts and clays to be transported as suspended load.

A relatively well-sorted silt was found in the shallow distributaries and marshes of the Mississippi River delta. This material was designated as Type IIb, and is thought to result from fractionation of the material supplied to the area by the river. Apparently sand size material is largely restricted to the deeper channels where it is transported as bed-load, and clay size material is retained in suspension and carried to deeper water beyond the delta front; leaving the silt size fraction of the river load to be deposited off the smaller distributaries and in the marshes.

In each area the distribution of sediments is dependent upon the type and amount of sediment supply and the processes of transportation, particularly the rigor of bottom agitation. In the vicinity of river mouths where sediment supply is great and the load may be relatively unsegregated, the type of sediment deposited is often directly related to the type of source sediment. Where rivers enter bays, as is the case in upper San Antonio Bay in the Rockport area, the bays act as settling basins and the finest material is found in the quiet, deeper portions of the bay. Small sandy beaches may occur along the perimeter of the bays where the fetch is sufficiently great to generate waves which segregate the fine material from the sands. Isolated beaches of this type are found in Aransas Bay at Goose Island and Blackjack Point, and in upper San Antonio Bay at Swan Point and McDowell Point. In the Mississippi delta area where the sediment supply is greater, and particularly where marsh deposits augment deposition and decrease wave efficiency, wave action is usually not of sufficient intensity to sort out the abundant fine material and form sand beaches. However, even in the Mississippi delta area there are places where waves are able to sort out material and form well-sorted sand beaches, as along outer portions of Southeast Pass.

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ECOLOGY OF THE BEAN CLAM *DONAX GOULDI* ON THE COAST OF SOUTHERN CALIFORNIA

By

WESLEY R. COE

Reprinted from *Ecology,* Vol. 36, No. 3, July, 1955

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ECOLOGY OF THE BEAN CLAM *DONAX GOULDI* ON THE COAST OF SOUTHERN CALIFORNIA[1]

During the past seventeen years the writer has examined at frequent intervals the successive populations of this little bivalve on the beach near the Scripps Institution and elsewhere. The times of arrival on the beach, the nature of the food, the rates of growth at various ages and seasons, the parasites, the maximum life-span, the arrival in certain years of almost incredible numbers and the sudden disappearance of these resurgent populations within two to three years, including both old and young individuals, have been the subjects of careful investigation.

Inspection of Fig. 1 will show that during the present century these resurgent populations have appeared on the beach at La Jolla at irregular and unpredictable intervals varying from two to fourteen years.

It is well known that other species of this genus in various parts of the world are likewise almost completely exterminated at intervals by the sudden death of apparently vigorous populations (Pelseneer 1928). It is only recently, however, that a satisfactory explanation for this unusual behavior of an animal population has been found and certain details of the problem remain to be elucidated. Coe (1953) has reported finding a minute unicellular organism in the tissues and cavities of the moribund individuals and these organisms were considered to be the causative agent of the deaths. Fitch (1953) mentioned such resurgent populations and their sudden disappearance.

Donax gouldi Dall is normally biennial on this part of the coast, although in certain years nearly all individuals have died after spawning when only one to one and one-half years old. In other years most individuals survive this first spawning period and die after spawning again in their second summer. There are also a few exceptional individuals which retain their vigor until they have completed a third spawning period in the spring or early summer of their third year. Most of the deaths have occurred during the warmest part of the year, that is, from June to September. Excessive numbers of dinoflagellates may sometimes contribute to the mortality.

The resurgent populations mentioned have been recorded at La Jolla in 1894-95, 1909-10, 1913-15, 1931-32, 1934, 1937-38 and 1949-52 (Coe 1953) and have doubtless occurred in earlier years (Fig. 1). In the resurgence of 1937-38 there were at least 10,000 clams per square meter in some areas in the intertidal zone, while the numbers in the 1949-52 resurgence averaged more than 20,000 per square meter in an irregular band 2 to 5 meters wide which extended with some interruptions for more than five miles along the beach. In addition to this

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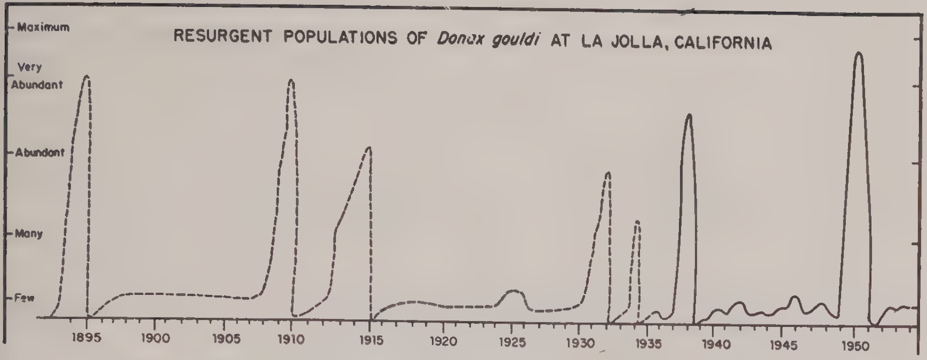

FIG. 1. Resurgent populations of *Donax gouldi* in the intertidal zone at La Jolla, California. Estimated relative abundance: "few," less than 5 per square meter; "many," 5 to 20; "abundant," more than 100; "very abundant," more than 1000; "maximum," more than 10,000 per square meter. The populations in the years preceding 1926 and from 1928 to 1936 (dashed line) are estimated from the incomplete records by Dr. W. E. Ritter, Mr. Percy Barnhart and others; those of 1926, 1927, 1937 and subsequent years from personal observations by the writer (solid line).

immense number in the intertidal zone, scattered individuals were found as far as 200 meters from the shore in water up to 6 meters in depth. In the immediately preceding year the numbers did not exceed one clam per square meter in the same locality. Precise data for the other resurgent populations reported are not available but the records indicate that they were similar, since large quantities were gathered for broth and poultry feed and in 1938 Donax clam broth was canned commercially at one locality.

After one to three years the populations have disappeared so completely that less than a dozen individuals have been found in an area occupied by millions a few months previously. The deaths have included not only the older members of the population but also the younger individuals which have arrived since the resurgence began. The history of one of these resurgent populations has been reported by Coe (1953) in this journal.

It has been mentioned that the life span of Donax in this locality is seldom more than two, or occasionally three, years and that fact might help to explain the deaths of the older members of the resurgent group but not those of all the younger individuals which settled on the beach subsequently. Examination of the moribund clams, both old and young, showed that their tissues were soft and slightly greenish in color, usually containing vast numbers of minute unicellular organisms. These organisms were found in the enlarged blood spaces and connective tissues, as well as within the phagocytes, within the cells of the digestive diverticulum, epithelium of gut, and in other organs.

Each of these parasitic organisms was found to be an irregularly spherical or ovoid cell, 2 to 6 μ in diameter and apparently similar to *Dermocystidium marinum* Mackin, Owen, and Collier, which causes so much destruction of oysters in the Gulf of Mexico and elsewhere along the southeast coast of the United States (Mackin 1951). As is also the case with the oyster disease, the disastrous effects of these parasites in Donax are evident mainly during the warmer months of the year.

Since the resurgent population may appear in a locality which was occupied by only a few individuals during several preceding years, it is concluded that vast swarms of larvae must have arrived from some other locality with a large breeding population. With a larval life of presumably two to three weeks or more, the free-swimming larvae may be carried for many miles by the ocean currents which on this coast have an average velocity of four to five miles a day. It may be assumed that the larvae reached the beach at the precise time when they were ready to metamorphose and settle in the sand. Preceding the arrival of the larvae at La Jolla it is known that there were spawning populations on beaches both north and south of that locality.

The young clams are first found in a broad band near the middle of the intertidal zone on a sandy coast fully exposed to the surf of the ocean. There they remain near the surface of the sand with their siphons projecting into the water whenever the sand is covered by water. They are later scattered widely by the action of the surf, principally to lower levels, and some are carried into water beyond the low-tide limit. The positions of the clams beneath the surface of the sand can often be detected by the projecting tufts of the hydroid Clytia.

Food. Whenever the clams are covered by water, they feed on particles of organic matter in suspension. These include small diatoms, dinoflagellates, bacteria, minute ova of invertebrates, spermatozoa, and a large proportion of detritus derived from the disintegration of animal and plant cells (Coe 1948).

Spawning. The first spawning commonly takes place at the age of about one year, or one and a half years for those hatched late in the season. The spawning season for the populations at La Jolla extends from April to October or November or six to seven months. Each female produces 1,000 to 50,000 or more yellowish ova at each ovulation and several ovulations may occur in the same year. Because of the extended spawning season, the average age of any year-class may be reckoned from the middle of July (Fig. 2).The young settle on the beach in greatest numbers from July to September.

Rates of growth. Increase in size is less rapid than in some other species, for the young clams average only about 12 mm. in length at the age of one year and 18 mm. at the age of two years. Most individuals on this beach have died after spawning during their second year.

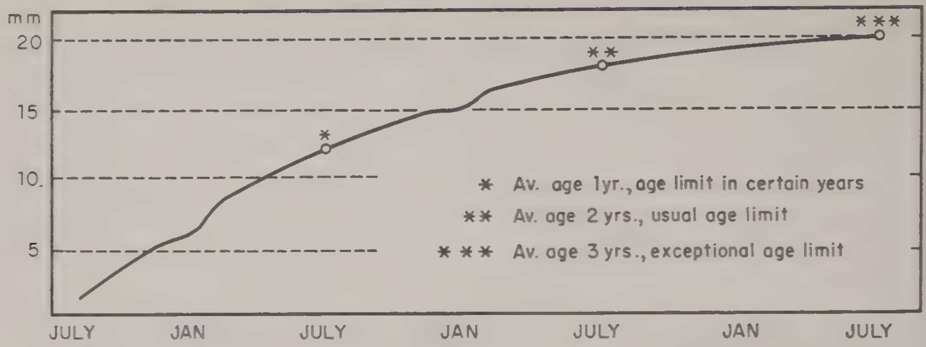

FIG. 2. Average rates of growth of *Donax gouldi* at La Jolla. Individuals which set on the beach in early July reached an average length of 12 mm. when one year of age and 18 mm. at the age of two years. The relatively few survivors were about 20 mm. long when they all died near the end of their third year.

The survivors average about 20 mm. in length at the extreme age of three years. Shells more than 24 mm. long are seldom found in this locality and in certain years the maximum size of spawning individuals is only 12-16 mm.

Enemies. Gulls devour vast numbers of Donax of all sizes and regurgitate the empty shells. The clams are eaten also by rays and by several species of fishes, notably corvina and the surf perches. These fishes frequently bite off and devour the siphons of the clams instead of taking their whole bodies.

Parasites. Many of the clams, and in some areas most of them, are infested with trematodes, particularly *Postmonorchis donacis* Young (1953). The parasites are first found in the visceral mass of the body and when present in large numbers encroach upon the gonads to such an extent as to render the clam more or less completely sterile but without apparent loss of vigor. The parasites evidently absorb the nutrition which would otherwise be available for the development of the gametes. The young parasites enter the connective tissue of the visceral mass and become sporocysts. These increase in size and produce the tailed cercariae. The latter give rise to the metacercariae which later encyst at the base of the siphons and edges of the mantle, as well as in the gills. The adults presumably live in the rectum of fishes (Young 1953).

A far more injurious parasite is the minute unicellular organism which sometimes contributes to the death of the entire local population, as mentioned in a preceding paragraph.

SUMMARY

This paper summarizes the results of observations during seventeen years on the habits and habitat, food, rates of growth at different ages and seasons, periods and conditions of spawning, enemies, and parasites. Data relative to the seven resurgent populations which have appeared on that beach in the past sixty years are included. In the resurgence of 1949 the population changed from an average of less than one clam per square meter to more than 20,000 within two months. An epidemic disease soon developed and the mortality became so great that within three years less than a dozen individuals, old or young, could be found in an area formerly occupied by millions. A minute unicellular organism was apparently responsible.

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The "Obscura Group" of the Genus Drosophila

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I. Introduction

The wealth of data collected in the last sixteen years and the importance of the results obtained by Dobzhansky and his coworkers have made *D. pseudoobscura* and related species living on the American continent a classical material for experimental studies of evolution.

In the last decade, studies on the European species belonging to the same natural group have also been developed by several workers from the viewpoints of taxonomy, genetics, cytology, and experimental evolution.

The present paper brings together both published and unpublished data with the purpose of offering a unified picture of the phylogenetic and distributional relationships between Eurasiatic and American members of the group.

Contributions from the Scripps Institution of Oceanography, New Series, No. 788

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II. TAXONOMIC HISTORY

During its first century, the history of *D. obscura* was uneventful from the taxonomic point of view, but during the last thirty years remarkable changes have taken place.

In 1823 Fallèn described a species of Drosophila from southern Sweden which he named *Drosophila obscura.* Its most easily recognizable characters, when compared with other European species, were its very dark body color and the presence of two sex combs on the front tarsi of the male. For about a century, specimens regarded as this species were collected by several systematists in Europe. It was not until 1916, however, that a related species was found in North America, when Sturtevant described *D. affinis*, found in the eastern part of the continent. Later (1921) he mentioned a species from the Pacific coast which seemed to fit Fallèn's description of *D. obscura.* Thus began the subsequent splitting of this taxonomic entity into nineteen described species to which at least three more forms should probably be added. All of them would fit the original description given in 1823.

In 1926 Frolowa pointed out that a strain of *D. obscura* collected in Russia had a chromosome set different from that described by Metz and Moses (1923) for the supposed American form of this species. She came to the conclusion, therefore, that it had been uncorrectly classified under this name. In a later study (Frolowa and Astaurov, 1929), it was shown that even though both forms could fit into the original description they could easily be distinguished on morphological as well as on biological grounds. As a consequence, the American form was considered as distinct from the European one, and was given the name of *D. pseudoobscura* Frolowa. These authors described at the same time another strain morphologically very close to what they considered as the true *D. obscura* but having a different chromosome configuration. This form, which had been studied for its sex ratio peculiarity by Gershenson (1928), was later considered as a different taxonomic entity under the name "*D. obscura* Gershenson" (Sturtevant, 1940).

In 1935 Dobzhansky described *D. miranda*, which occurs more or less continuously along the Pacific coast from Vancouver Island to the Monterey Peninsula and in isolated localities of the Sierra Nevadas. This species was morphologically indistinguishable from *D. pseudoobscura* but can be crossed to it, giving F_1 hybrids which are mostly sterile. In the following year, five more species (*algonquin*, *athabasca*, *azteca*, *narragansett*, and *seminole*) were found on the North American Continent and described by Sturtevant and Dobzhansky (1936).

In England, at the same time, Collin (1936) found an *obscura*-like form which can be easily distinguished from the type of *D. obscura* Fallèn. This species was accordingly named *D. subobscura.*

In 1937 Dubinin, Sokolov, and Tiniakov published a paper on the chromosome structure of Drosophila species occurring in Russia. They spoke of a "*D. obscura,*" a "*D. obscura*-2" and a "*D. obscura*-3." On the basis of the few morphological and cytological details published by them, one can surmise that *D. obscura*-3 of the Russian authors corresponds to *D. subobscura* Collin. This interpretation was confirmed by a later note (Sokolov and Dubinin, 1941).

In 1938 Buzzati-Traverso collected a large series of flies in northern Italy and Germany which also corresponded to Fallèn's description. All possible crosses between the different strains were made and it was found that the collected material fell into five distinct groups which could not be crossed with one another. One of these forms was identified as *D. subobscura* Collin, and another was first regarded as the variety *tristis* of *D. obscura* Fallèn, but was later raised to specific rank as *D. tristis.* The whole material was handed over to Pomini (1940) who described and named the three remaining forms as *D. ambigua, D. bifasciata** and *D. obscuroides.* Reference to the name *D. obscura* was avoided, for it was uncertain whether any of them was identical with Fallèn's type, the war preventing comparison with type specimens. The following year a description of the mitotic chromosomes of these five species was published by Buzzati-Traverso (1941b) together with a discussion of the possible taxonomic relationships between them.

Two more species from the North American continent, also related to *obscura,* were later named *D. dobzhanskii* (Patterson, 1943) and *D. tolteca* (Patterson and Mainland, 1944).

In 1929 Lancefield distinguished two races (A and B) of *D. pseudoobscura* on the grounds of chromosome morphology. This distinction was later confirmed by cytological and genetic investigations of Dobzhansky and Boche (1933) who found that the two races were intersterile. The latter distinction later (1944) led to the segregation of race B as *D. persimilis* Dobzhansky and Epling, even though it was morphologically indistinguishable at the time (Mather and Dobzhansky, 1939). Ritzki has only recently (1951) found a consistent difference in the male genitalia of the two species.

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* In Pomini's description (1940), a systematic account of the new species *D. bilineata* is given. This name is used by Pomini throughout the paper, but in the determination key (page 163) the same fly is referred to as *D. bifasciata.* Buzzati-Traverso pointed out (1948b) that, since the name bilineata had been previously used by Williston for a quite different species (see Sturtevant, 1921), the species described by Pomini and belonging to the European "obscura group" should be named *D. bifasciata* Pomini.

In 1945 Smart pointed out that a species found in Kenya and named *D. subobscura* by Seguy (1938) had to be given another name, inasmuch as *D. subobscura* was previously chosen by Collin to describe a form certainly distinct from the African one. Smart accordingly named the latter *D. seguyi* Smart.

Two more European species of the group, *D. helvetica* and *D. alpina*, were described in 1948 by Burla. Finally in 1949 Wheeler found another species in North America and named it *D. frolovae.*

Thus a complex of 19 species has been described, all closely related to the first named, *D. obscura.*

The question has been recently raised by Buzzati-Traverso (1949b) as to which of the species referred to in this discussion should be regarded as synonymous with *D. obscura* Fallèn. Living material collected through the kind offices of Prof. K. Anders, University of Lund, at Esperöd (Sweden), the *terra typica* of *D. obscura,* was a mixture of *D. obscuroides* and *subobscura.* Comparison of the male external genitalia of several species with those of Fallèn's type, labeled *D. obscura* in his own handwriting, was later made by Cain, Collin, and Demerec (1952) and proved that *D. obscuroides* Pomini is synonymous with *D. obscura* Fallèn. Thus, two lines of evidence indicate beyond doubt that the name *D. obscura* Fallèn should be correctly applied only to the species described as follows (according to Pomini, 1940; Buzzati-Traverso, 1941b; and Burla, 1951):

Drosophila obscura Fallèn, described in 1823, has the synonyms *D. obscura*-1 Frolowa (1929) and *D. obscuroides* Pomini (1940).

Male: Arista with 7 branches. Second joint of the antenna yellow-brown, with brown spot on the posterior side; third joint dark brown. Front opaque dark brown, with anterior part lighter. Orbits and ocellar triangle shining brown. Second orbital ⅓ of the third. Second oral bristle ⅓ of the first. Face and proboscis yellow. Brownish palpi; brown, broad, and high carina. Cheeks brownish yellow, their greatest width about ⅓ greatest diameter of eyes. Eyes dark red.

Mesonotum and scutellum brown, pollinose, with grayish and bronze colored reflexes. Two dark brown shining longitudinal stripes, from scutellum to neck, between dorsocentral bristles. The conspicuousness of the stripes varies with age. Sometimes, instead of the two stripes, one single broad, dark stripe extends forward from the scutellum.

Scutellum dark brown with lighter margins. Pleurae dark brown, 8 rows of acrostichal hairs. Sterno-index about 0.55. Apical bristles on first and second tibiae, preapicals on all. Small comb of short, stout, curved, black bristles, obliquely placed with respect to the main axis of the joint, on the inner side of each of the two basal joints of each front tarsus. Wings clear, veins brownish-yellow. There are 2 bristles in front of the costal break. Stout costal bristles over ⅖ of the third costal section. Costal index about 2.9, fourth-vein index about 1.9, 4c index about 0.9, 5x index about 1.5.

Abdominal tergites dark brown. A series of about 9 black, tooth-shaped bristles on each of the forcipes.

Length of body: 2.4–3.7 mm, 2.2–3.1 mm; length of wings: 2.4–3.3 mm, 2.2–2.8 mm.

Females agree, except no tarsal combs. Yellow spots on the sides of the 4–6 tergites, in anterior marginal position.

Internal characters of imagines: Testes dull orange; proximal portion sac-like, short, and thin; distal portion elliptic, large. Spermathecae spherical, chitinized. Ventral receptacle, N-shaped tube, lying against the ventral surface of the uterus. Anterior and posterior arms of Malpighian tubules free.

Eggs: 2 filaments, with distal ends expanded.

Puparia: Yellow brown, each anterior spiracle with 8–10 branches.

The above is a chronological history from a purely nomenclatorial viewpoint. In 1942, however, Sturtevant brought the classification of Drosophila up to date and proposed a subdivision of the genus Drosophila into several subgenera, some of which were further subdivided into "species groups." According to Sturtevant's data, the species referred to above belong to the "*obscura* group" of the subgenus Sophophora.

The *obscura* group includes dark species with the following characters (Patterson and Stone, 1952):

"No opaque areas on tergites, sex combs present, preapical on first tibiae usually long, sterno-index 0.6, anterior scutellars convergent, second oral bristle small, middle orbital bristle large, and larvae do not skip."

The group is subdivided into two subgroups (Table 1): *obscura* subgroup, forms with several teeth in the distal sex comb, acrostical hairs in eight rows, ventral receptacle short, testes elliptical and carina broad and flat; *affinis*-subgroup, forms with one or two teeth in the distal sex comb, acrostical hairs in six rows, ventral receptacle nearly as long as in the *melanogaster* group, testes rather short and spirally coiled, carina narrow and not flat.

Besides the described species, there certainly are others of this group which await description. Such are, for example, *obscura-X* mentioned by Burla (1951), another form found in Scotland which will be called *D. silvestris* (Basden, personal communication) and probably one undescribed species close to *D. athabasca* found in Japan (Makino *et al.*, 1952). In the following discussion of the taxonomic, cytologic, and genetic relationships of the species belonging to the *obscura* group, only those species will be considered which are known from living material, and have thus made careful biological studies possible. The genus Drosophila has provided an exceptional material for evolutionary studies (see Patterson and Stone, 1952) because of the unparalleled qualities of many of its species: short life cycle, remarkable fecundity and hardiness, ease and cheapness of rearing, unusual cytological material. It is our opinion that the most reliable conclusions about relationships between species can be drawn not from morphological similarities alone, but only when they are supported by experiments which disclose their reproductive and cytological compatibilities.

TABLE 1

Species of Drosophila Belonging to the *Obscura* Group

obscura subgroup	*affinis* subgroup
Nearctic forms	Nearctic forms
frolovae Wheeler, 1949*	*affinis* Sturtevant, 1916
miranda Dobzhansky, 1935c	*algonquin* Sturtevant et Dobzhansky, 1939
persimilis Dobzhansky et Epling, 1944	*athabasca* Sturtevant et Dobzhansky, 1936
pseudoobscura Frolowa et Astaurov, 1929	*azteca* Sturtevant et Dobzhansky, 1936
Palaearctic forms	*dobzhanskii* Patterson, 1943*
alpina Burla, 1948*	*narragansett* Sturtevant et Dobzhansky, 1936
ambigua Pomini, 1940	*seminole* Sturtevant et Dobzhansky, 1936*
bifasciata Pomini, 1940	*tolteca* Patterson et Mainland, 1944*
obscura Fallèn, 1823	Palaearctic forms†
silvestris Basden, 1954	*helvetica* Burla, 1948
subobscura Collin, 1936	
tristis Fallèn, 1823	
obscura-X Burla, 1950	
Ethiopian form	
seguyi Smart, 1945*	

* Not reared in the laboratory.

† A species close to *athabasca* has also been found (Makino *et al.*, 1952a, undescribed).

III. The Nearctic Members

Numerous papers of a detailed sort as well as reviews of the American representatives of the *obscura* group are available. We will not, therefore, enter into a discussion of these species except for data pertinent to topics to be discussed presently and we will refer the reader especially to the following publications, Dobzhansky and Epling's "Taxonomy, Geographic Distribution, and Ecology of *Drosophila pseudoobscura* and Its Relatives" and Patterson and Stone's "Evolution in the Genus Drosophila."

1. *Geographic Distribution*

The four American species belonging to the *obscura* subgroup occur chiefly west of the continental divide (Fig. 1). *D. pseudoobscura* has the widest range, the northernmost localities are in British Columbia and the southernmost in Guatemala, it ranges west of the main mountain chains to the Pacific coast and on islands off it. *D. persimilis* occurs from Vancouver Island and central British Columbia to south central California, and from the Pacific to the eastern slope of the Sierra Nevada

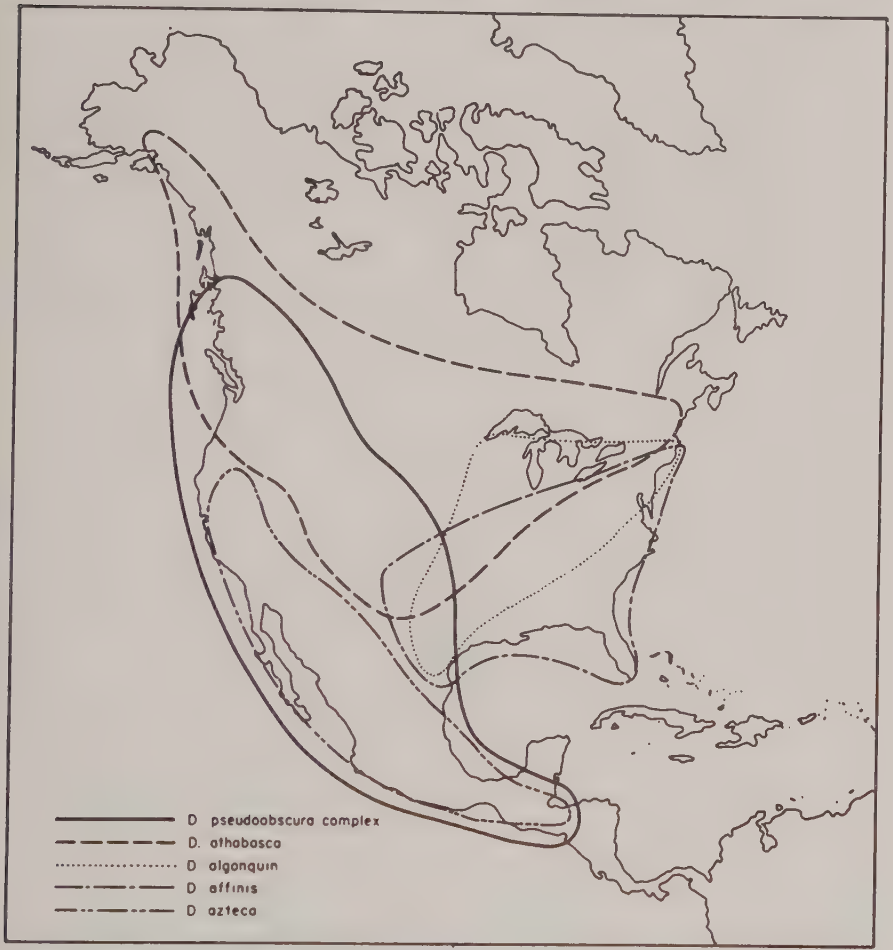

FIG. 1. Distribution of the most representative species of the *obscura* group in the Nearctic region (based on data by Patterson and Wagner, 1943).

and Cascade ranges; it is also found in the Coso and Panamint ranges. *D. miranda* is distributed more or less continuously along the Pacific coast from Vancouver Island to the Monterey Peninsula. It has also been found in an isolated locality in the Sierra Nevadas, and quite recently in the San Jacinto Mountains (Epling, personal communication). *D. frolovae* has been found only once in a forest in the mountains about 19 miles east of Morelia, Michoacan, Mexico.

The distribution of *affinis* subgroup is wider and more varied. *D. athabasca* has been recorded as far north as Alaska, as far south as New Mexico, and extends from the North Pacific coast to the eastern slope of the Rocky Mountains and to Tennessee. *D. azteca* has been recorded in Guatemala, in several Mexican states, and in Texas, New Mexico, Arizona, and California. *D. affinis* and *D. algonquin* seem to have an overlapping distribution covering the South, the Middle West, and the Eastern United States. *D. narragansett* has been found in Massachusetts, Connecticut, Ohio, and Texas. *D. dobzhanskii* and *D. tolteca* seem to be limited to some areas in Mexico. *D. seminole* has been recorded only from Alabama.

2. *Chromosomes*

The metaphase configurations of American members of the *obscura* group are presented in Fig. 2. A detailed summary of the cytological evidence on the subject is given by Patterson and Stone (1952, pp. 130–133 and 191–207). Here mention will be made only of the following points: (1) The members of the *obscura* subgroup have basically the same metaphase configuration, with one dot and the five long elements, basic to the genus Drosophila, arranged in three rods and one V-shaped chromosome, derived by the fusion of elements A and D of Muller's classification (1940). *D. miranda* has a peculiar sex-determining mechanism with two X chromosomes. (2) The members of the *affinis* subgroup show three different configurations, in which the X chromosome is derived from the fusion of elements A and D, and the autosomes have various shapes as a result of pericentric inversions and addition of heterochromatin in the basic remaining elements. (3) In the salivary gland nuclei, heterochromatin is mostly concentrated in the chromocenter, always well evident. (4) More than one gene arrangement has been found in every chromosome of the studied species, except chromosome C (element B) in *D. azteca.* (5) Element C shows a higher variability than the other chromosomes in *D. pseudoobscura* and *D. persimilis* (Chromosome 3), *D. athabasca* (Chromosome C) and *D. azteca* (Chromosome A), whereas in *D. algonquin* all the chromosomes have a uniformly low variability. (6) This variability in element C has allowed the reconstruction of a

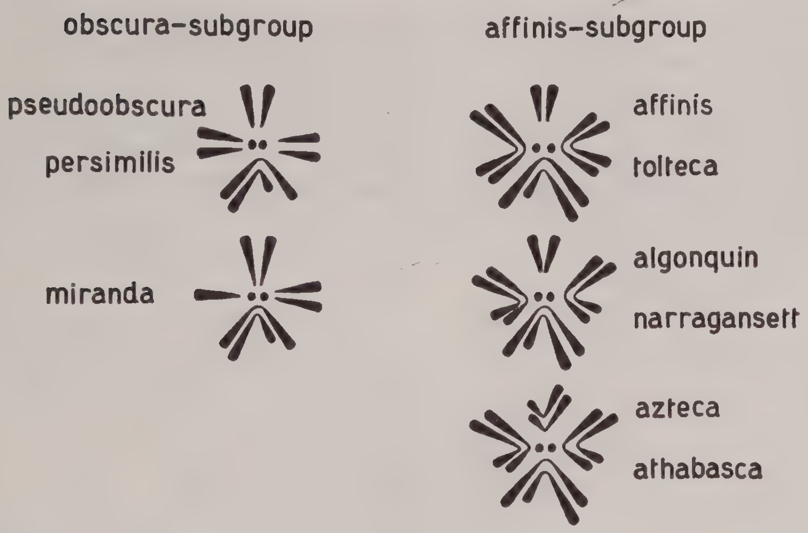

Fig. 2. Metaphase configurations of Nearctic members of the *obscura* group.

very convincing chromosome phylogeny for the complex *pseudoobscura-persimilis-miranda* and for *D. athabasca*.

3. *Genetics*

The genetics of the complex *D. pseudoobscura-persimilis-miranda* has been worked out by Lancefield (1922), Tan (1935b, 1936), and Dobzhansky and Tan (1936); genetic data on *D. affinis* have been discussed by Sturtevant (1940). These works made it possible to establish homologies between the chromosome elements of these species and those of *D. melanogaster* and other species, thereby showing the genetic relationships between members of the *obscura* group and of other groups and subgenera (Muller, 1940; Sturtevant and Novitski, 1941). Homologies between *D. affinis* and other species of that subgroup have been based on cytological studies (Miller, 1939; Dobzhansky and Sokolov, 1939).

IV. The Palaearctic Members

Taxonomic descriptions of the European members of the *obscura* group has been given by Collin (1936), Pomini (1940), and Burla (1948, 1951).

1. *Geographic Distribution*

The range is fairly well known for western Europe, but scarcely at all for eastern Europe and Asia. More extensive information about this vast area is badly needed, for we know that at least two members of the group occur as far east as Japan and at least one as far south as Lebanon

(Basden, 1952, 1954; Burla, 1948, 1951; Burla *et al.*, 1950; Buzzati-Traverso, 1941b; Hadorn *et al.*, 1952; Makino *et al.*, 1952a,b; Moriwaki *et al.*, 1951, 1952a,b, 1953; Pipkin, 1951; Pomini, 1940; Prevosti, 1952).

D. obscura (Fig. 3) has been found practically everywhere in Europe, at all elevations, from the Atlantic coast to central Germany (Berlin) and eastern Austria, as far north as Scotland and southern Sweden and as far south as the Ebro river in Portugal and the Po Valley in Italy. It apparently does not occur further east, except perhaps in European Russia. This conclusion is based on Gershenson's report (1928) of finding two females of *D. obscura* near Moscow (Zvenigorod). A few generations consisting almost exclusively of females were reared and were studied cytologically by Frolowa. She found that the chromosome set was comparable to that of *D. obscura*. The entities ascribed to *D. obscura* by Frolowa and Astaurov (1929) from the neighborhood of Moscow, and by Dubinin, Sokolov, and Tiniakov (1937) from Moscow, Alma Ata (Semirechije) Gori (Transcaucasia) and Samarkand (central Asia) are *D. bifasciata* (see below). The species is very frequent in woods and bushes, and prefers a rather humid environment, being very rare in dry areas, and in clearings.

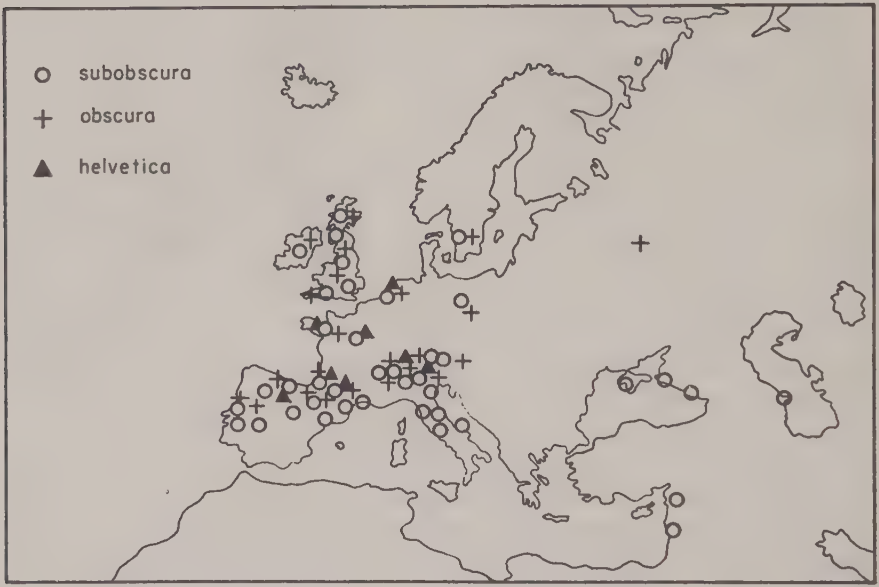

FIG. 3. Distribution of the known records for Europe of *D. subobscura* and *D. obscura*, belonging to the *obscura* subgroup, and of *D. helvetica*, belonging to the *affinis* subgroup.

D. subobscura (Fig. 3) is by far the most commonly collected species in western Europe. It has been recorded all over Europe from the Atlantic coast to the Black and Caspian seas and from Scotland and Sweden to southern Italy, Syria, and Lebanon. It occurs from the sea level to timber line and can be found wherever trees or bushes are present.

D. ambigua (Fig. 4), too, has been found in very different ecological conditions such as the dry climate of southern Europe (Iberic and Italian peninsulas, Sardina) and the more humid conditions of northern France, Holland, and Great Britain. It has been found as far east as Austria.

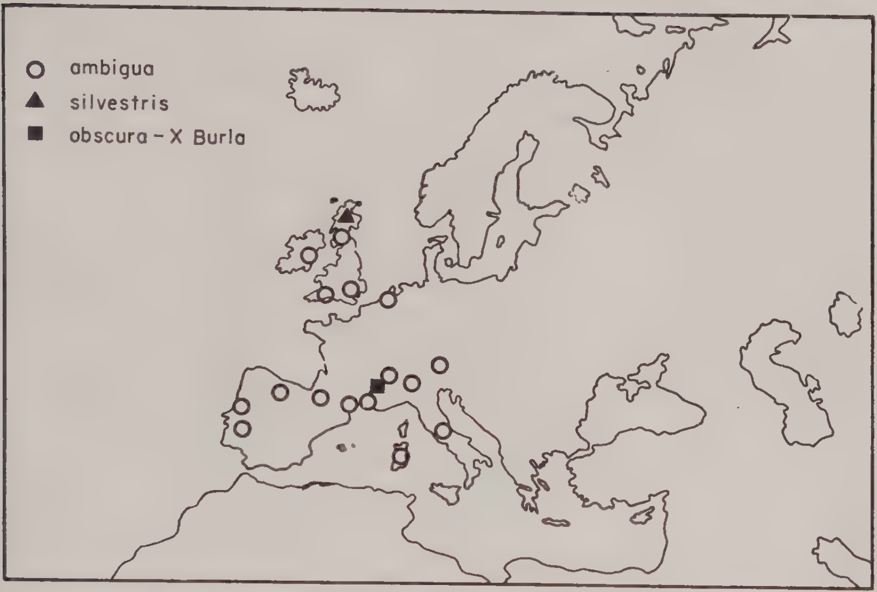

FIG. 4. Distribution of the known records of *D. ambigua*, *D. silvestris*, and *D. obscura-X*, Burla, belonging to the *obscura* subgroup.

D. bifasciata (Figs. 5 and 6) has been found in France, Germany, the Iberic peninsula, Italy, Switzerland, Holland, and has recently been captured in northern Japan where it is the most abundant species all over the mountain districts throughout the year (Moriwaki *et al.*, 1951, 1952a,b, 1953). The species from Russia referred to *D. obscura* by Frolowa and Astaurov (1929) and by Dubinin, Sokolov, and Tiniakov (1937) is considered to be *D. bifasciata* for the following reasons: (1) identity of the metaphase chromosome configurations; not only does the general description of Frolowa correspond well to that of Buzzati-Traverso, but the peculiarity of the dot chromosome being somewhat larger than in most Drosophila species is emphasized independently by both authors;

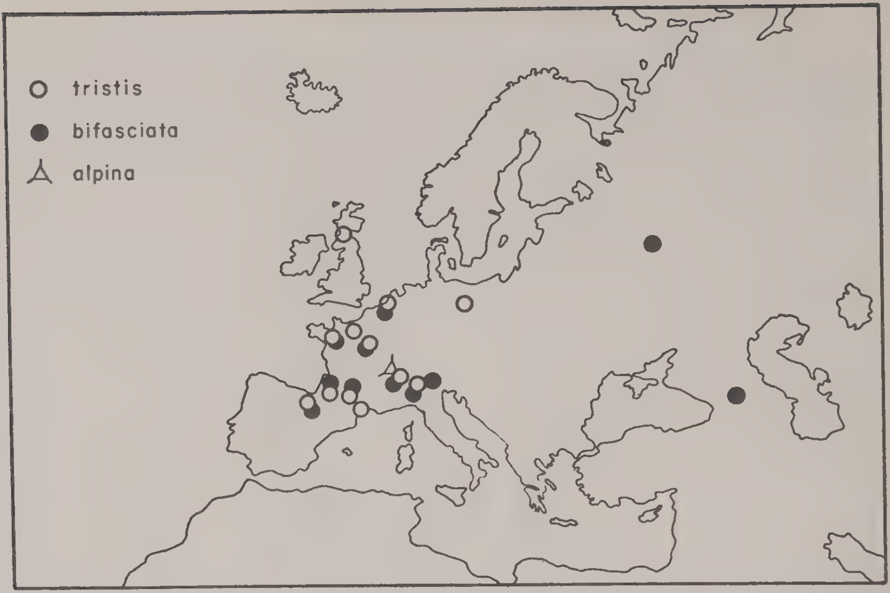
○ tristis
● bifasciata
⅄ alpina

FIG. 5. Distribution of the known records for Europe of *D. tristis*, *D. bifasciata*, and *D. alpina*, belonging to the *obscura* subgroup.

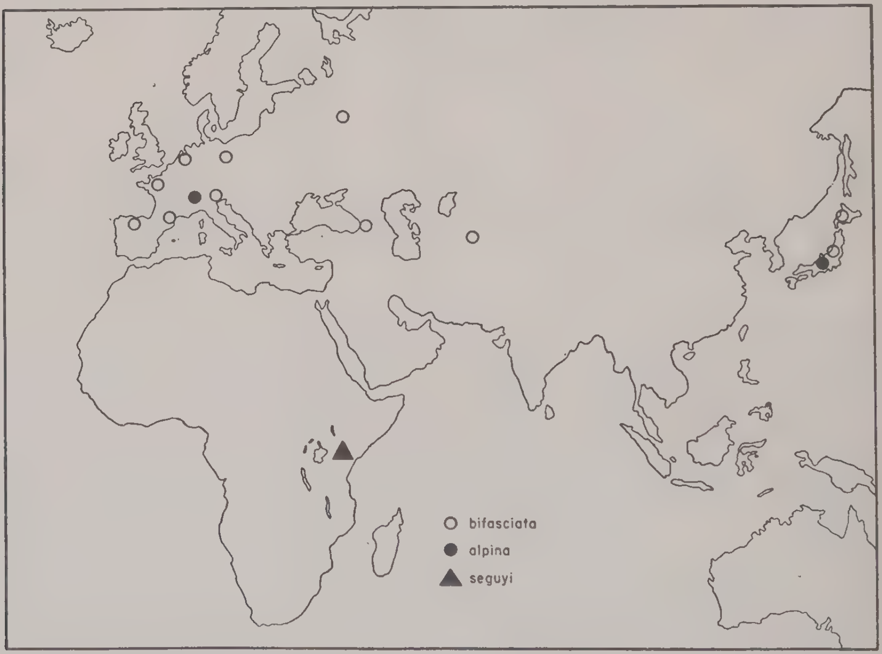
○ bifasciata
● alpina
▲ seguyi

FIG. 6. Distribution of the known records for the Palaearctic region of *D. bifasciata* and *D. alpina*, and of *D. seguyi* for the Ethiopian region.

(2) the correspondence in the number of teeth on the clasper's combs (10) in Frolowa and Astaurov's as well as in Pomini's and Burla's description; (3) the correspondence in the teeth number of sex combs on male tarsi. It seems, therefore, that *D. bifasciata* occurs more or less continuously in Eurasia from the Atlantic to the Pacific. It is accordingly the member of the *obscura* group with the widest range for it comprises the whole Palaearctic.

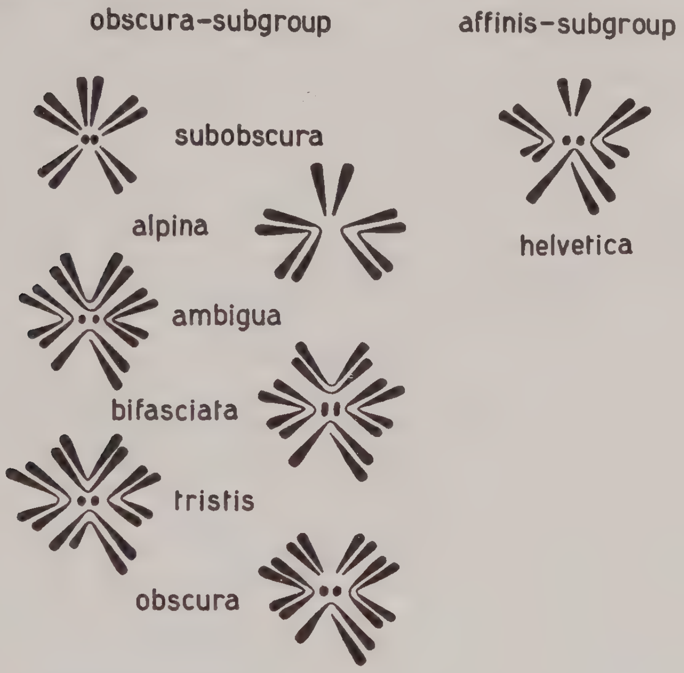

FIG. 7. Metaphase configuration of Palaearctic members of the *obscura* group.

D. tristis (Fig. 5) has been found in Scotland, Cornwall, France, Spain, Pyrenees, Holland, Switzerland, and northern Italy. Its area is discontinuous, however, because it is confined to very humid areas in the neighborhood of rivers and springs, irrespective of altitude.

D. alpina (Fig. 5) has been certainly recorded only for Switzerland and more recently for Japan.

D. helvetica (Fig. 3) has been found only in France, Holland, Germany, Switzerland, and in Italy on the southern slopes of the Alps.

2. *Chromosomes*

The metaphase configurations of Palaearctic members of the *obscura*-group are given in Fig. 7. They have been described by Frolowa and

Astaurov (1929), Emmens (1937), Buzzati-Traverso (1941b), Philip (1941), Burla (1950), and Moriwaki *et al.* (1952b, 1953). Salivary gland chromosome maps are available for *subobscura* (Frizzi, 1950; Mainx, Koske, and Smital, 1953), *ambigua* (Mainx *et al.*, 1953; Frumento, 1954), and *obscura* (Mainx, Koske, and Smital, 1953). A comparison of the salivary gland chromosomes of the last two species and of *bifasciata* and *tristis* has been given by Prevosti (1950).

The only species belonging to the *affinis* subgroup has a metaphase configuration similar to that of some of the Nearctic species of the group. Salivary gland chromosomes have not been studied.

The members of the *obscura* subgroup show a variety of patterns. *D. subobscura* has the cytological configuration that has been considered as the basic for the genus (Muller, 1940; Sturtevant and Novitsky, 1941), i.e., five rods and a dot, the Y chromosome has the same length as the X. *D. alpina* has only three chromosomes, i.e., one rod and two V-shaped chromosomes, probably derived from two fusions of four of the long elements. This is the only species of the *obscura* group that does not have the dot chromosome, and has been recently confirmed by Kurokawa through examination of larval ganglion and salivary gland cells (Moriwaki, personal communication). *D. ambigua* and *tristis* have a similar set, with a V-shaped X chromosome, probably derived from the fusion of two basic elements (see discussion in Section VII), three V-shaped autosomes and one dot. The former species has a rod-shaped Y, while the latter has a J-shaped Y chromosome. *D. bifasciata* has a similar arrangement, but differs from the last two species in that the limbs of the X chromosome are shorter and the small chromosome looks more like a short rod than like a dot. This unusual shape is probably due to the presence of heterochromatin, since this element does not seem particularly elongated in the salivary gland chromosomes. The Y chromosome is rod shaped. As pointed out in Section IV, 1 of this paper, the morphological and cytological description of Russian "obscura" corresponds to that of *D. bifasciata;* this Russian form should be considered as belonging to the said species and with the just described chromosome set. *D. obscura* has three V-shaped chromosomes, one of which is the X, two rods and one dot; the Y chromosome is rod shaped. This configuration corresponds to that given for the so-called "*obscura* Gershenson," as pointed out by Buzzati-Traverso (1941b, also see Section IV, 1 of this chapter); this Russian form should accordingly be considered as *D. obscura.*

While the remaining species have a very easily distinguishable chromocenter, *D. subobscura* salivary nuclei have practically no such structure. The salivary chromosomes of this species have, on the other hand, a striking amount of heterochromatin distributed in intercalary position

(Frizzi, 1950); this originates the formation of "puffs" which make the observation of chromosomes difficult, particularly in aged larvae. Natural populations of *subobscura* show a very remarkable amount of chromosome variability. At least 40 different inversions have been recorded and practically every individual is heterozygous for more than one inversion; the five long chromosomes are affected (Stumm-Zollinger, 1953; Mainx, Koske, and Smital, 1953, and unpublished data). Observations in nature, as well as experimental tests, indicate that this extreme polymorphism in the gene arrangements is sustained not merely by a selective advantage of the inversion heterozygotes, as demonstrated for one inversion in chromosome 5 by J. and S. Maynard Smith (1954), but by the presence of balanced lethals. This conclusion is proved by the following facts: (1) Practically every studied larva descending from free-living females has proved to be heterozygous for more than one inversion involving the five chromosomes. Sokolov and Dubinin (1941) as well as Philip *et al.* (1944) have accordingly regarded this species as a permanent hybrid. (2) In the inbred progeny of flies captured in the wild a great amount of embryonic mortality is observed, which has made the breeding of some strains especially hard (Buzzati-Traverso, 1941a; Frizzi, 1950, and unpublished data); accordingly, attempts to secure strains homozygous for certain inversions have failed. (3) The only free-living individuals found that were structurally homozygous in all the five chromosomes, even though captured at such widely separated localities as Küsnacht, Switzerland (Zollinger, 1950), Esperöd, Sweden, Mergozzo, Italy (unpublished data), and Alpach, Austria (Mainx, Koske, and Smital, 1953), all proved to have the same gene arrangement. This is probably the only one viable in homozygous condition. The chromosomal polymorphism found in *D. subobscura* populations does not seem to be correlated with the ecological characteristics of the habitat occupied by the species (Stumm-Zollinger, 1953).

No comparable amount of work has been concentrated on the study of chromosome variability in the remaining five species. Disregarding *D. alpina* for which no data at all are available, it can be said, however, that inversions have been found in every case. According to reports of the Austrian geneticists, it appears probable that the amount of chromosomal polymorphism of *D. tristis* is comparable to that of *subobscura*, while that of *ambigua*, *bifasciata*, and *obscura* is much more limited.

3. *Genetics*

The present knowledge of the genetics of Palaearctic species of the group under discussion is satisfactory for only one species, *D. subobscura*. An imposing amount of data has been collected on this species during the last eighteen years at the Department of Biometry of the University of London. Thanks to the efforts of these workers (Biometry Department, 1946, 1948, 1949; Bird, 1946a,b; Boyd *et al.*, 1939; Christie, 1939; Clarke, 1951, 1952; Fahmy, 1952; Goldberg, 1950; Gordon, 1936; Gordon *et al.*, 1939; Haldane, 1945; Hipsch, 1952; Hornibrook, 1952; Jermyn *et al.*, 1943; Milani, 1949; J. and S. Maynard Smith, 1952, 1954; Philip, 1941, 1946; Philip *et al.*, 1944; Rendel, 1943, 1945; Rendel and Spurway, 1940; Rendel and Suley, 1946; Spurway, 1939a,b, 1945, 1946a,b, 1948, 1951; Spurway and Haldane, 1954; Spurway and Philip, 1952; and Suley, 1953) it is now possible to establish genetic homologies between American and European species. Unfortunately the data have never been summarized, so that it is necessary to bring together bits of information which are scattered through several papers and in notes published in the Drosophila Information Service, 1946, 1948, 1949; Mainx, 1949, 1950; Prevosti, 1952.

A total of 233 mutants have been reported. Of these, 79 have not been localized. The remaining belong to the various chromosomes as follows (the terminology of Dr. H. Spurway-Haldane will be used): chromosome X, 94 visible mutants, 2 lethals, 29 loci; chromosome 2, 20 visible mutants, 13 loci; chromosome 3, 7 visible mutants, 5 loci; chromosome 4, 15 mutants, 11 loci; chromosome 5, 15 mutants, 8 loci; chromosome 6, 3 mutants, 3 loci. On the basis of the parallelism shown by the phenotype of some of these localized mutants with respect to that of mutants known in other species, it has been possible to establish the following homologies:

Chromosome X (e.g., bobbed, cut, crossveinless, dusky, lozenge, miniature, scute, singed, white, yellow) corresponds to element A.
Chromosome 2 (e.g., scarlet, sepia, hirsute, interrupted) corresponds to element D.
Chromosome 3 (e.g., net) probably corresponds to element B.
Chromosome 4 (e.g., plexus, poppy, pointed) corresponds to element C.
Chromosome 5 (e.g., aristapedia, Bare, Delta, vermilion) corresponds to element E.
Chromosome 6 corresponds to element F.

It appears worth while to point out a peculiarity of the genetic map of Chromosome X, namely that of having just one limb and over 200 Morgan units.

For the remaining species very little is known. For *D. ambigua*, 9 visible mutants have been reported (Mainx, 1950a, 1951), for *D. bifasciata*, 8 visible mutants (Buzzati-Traverso, 1951a; Mainx, 1952a), for *D.*

obscura, 4 visible mutants (Mainx, 1950b), and for *D. tristis*, one mutant (Mainx, 1952b).

4. *Biology*

We will report here on some biological peculiarities of European members of the *obscura* group which seem of significance for the discussion to follow.

D. subobscura. As shown by Rendel (1945), this species is unable to mate in total darkness. Only one other Drosophila species, *D. auraria*, is known to have a similar behavior. Even though occurring in very hot climates such as in Lebanon, Syria, and southern Italy, *D. subobscura* seems to be very sensitive to high temperatures for it becomes easily sterile in the laboratory at about 25°C, and females prefer relatively low temperature (about 19°C) for egg laying.

Remarkable differences in sensitivity to temperature can be found within the distribution range of the species. Buzzati-Traverso (1941a) found two extreme "temperature races" in this species. An English race became sterile at more than 21°C, and a northern Italian one has its developmental optimum at 23°C.

Natural breeding habitats for *D. subobscura* are on record, these being the only ones for the European members of the *obscura* group. Specimens of these species were reared from diseased iris roots by Collin in England, as reported by Smart (1945). Buzzati-Traverso (1948c) found larvae of *D. subobscura* in several localities in northern Italy crawling in the fermenting pulp of cornel berries (*Cornus* sp.) decaying on the soil in mixed woods. A similar habitat has been reported on galls of *Biorrhiza pallida* (Oliv.) formed on oaks in southern England (Basden, 1952). Wild yeasts have been isolated from free living individuals and were shown to be preferred to baker's yeast by *D. subobscura* (Buzzati-Traverso, 1948d, 1949a).

As previously pointed out, *D. subobscura* is the prevailing species of this group in western Europe, followed by *D. obscura* in order of dominance. Both species can be considered as eurytopic forms. As shown by Burla (1951), however, *D. obscura* and *D. subobscura* show minor differences in their ecologic valence with respect to their distribution in various biotopes at different altitudes (see Fig. 8).

D. bifasciata is peculiar in that a large fraction of its wild females produce almost exclusively female progeny (Buzzati-Traverso, 1941c). This sex-ratio condition is transmitted through the female line and is probably dependent on the presence of a cytoplasmic factor which does not allow for the embryonic development or metamorphosis of Y-bearing zygotes (Magni, 1952, 1953a,b). This condition has been found in several wild populations, its frequency among free-living females being as high as 30% in one locality. A similar condition was observed once in the progeny of *D. obscura* females collected in northern Italy (Magni, 1952). The accidental loss of the strain prevented a detailed analysis. A different type of sex-ratio condition was described by Gershenson (1928) for a strain of a species collected in Russia. On the basis of the cytological description given by Frolowa, it is possible to say that this was *D. bifasciata*. In this case the sex-ratio condition was due to a gene producing abnormalities in the meiosis of males which could not produce Y-bearing sperms.

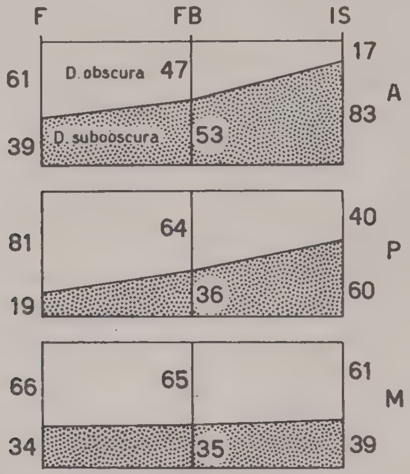

FIG. 8. Differences in the ecological valence of *D. obscura* and *D. subobscura* in various biotopes at different altitudes in Switzerland. The frequencies are given in relative percentage of the two species for: the Alps (A), the Pre-Alps (P) and for the region comprised between the Jura and the Pre-Alps (M); in the forest (F), at the edge of forests (FB), in meadows with scattered trees (IS) (from Burla, 1951).

V. MATING BEHAVIOR

The mating behavior of the considered species follows a basically similar pattern. There are, however, two major variations on the same theme which enable us to separate the species of the *obscura* group into two subgroups, which fit very well into the morphologic distinction of *obscura* and *affinis* subgroups.

The basic mating behavior of the group consists (Spieth, 1952) of "the male's tapping, followed by posturing at the side, front, or rear of the female, but never involves licking at any time. The female accepts by spreading the vaginal plates but not the wings. The male achieves intromission by grasping the dorsolateral surface of the female's abdomen with his forelegs and bringing the tip of his abdomen forward and under;

he then immediately mounts and spreads the female's wings with his forelegs, aided by the sex combs. The male assumes a 'forward' copulatory position, holding onto the bases of the female's wings with his fore tarsal claws".

The differences between the two subgroups, *obscura* and *affinis*, are related to the actions performed by the male just after "tapping". Those of the *obscura* subgroup posture at the side, front, or rear of the female, while the males of the *affinis* subgroup circle the female but never posture in front of her.

Minor differences in the mating behavior have been described for each of the species of the group (Milani, 1950, 1951a,b; Weidmann, 1951; Spieth, 1952). It should be pointed out that *subobscura* not only stands out with respect to the rest of the species of the group for its requirement of light in order to perform mating (Philip *et al.*, 1944; Rendel, 1945; Wallace and Dobzhansky, 1946; and Milani, 1951a) but that it shows a peculiar behavior in terms of posturing action when compared with the remaining European species of the *obscura* subgroup. As we shall see later, *subobscura* is divergent from these in some morphological traits, too.

According to Spieth, *subobscura* engages a posturing movement which is almost identical to that of *pseudoobscura*, *persimilis*, and *miranda*. This author therefore concludes: "this movement is so distinct and so similar in all four species that it seems logical to conclude that this element of the mating behavior was possessed by an ancestor common to all four species".

VI. Interspecific Hybrids

Attempts to obtain hybrids among species of Drosophila have proved very useful for ascertaining the degree of genetic affinity and the possible phylogenetic relationships between the tested entities (*e.g.*, Patterson and Stone, 1952). Numerous tries of this sort have been made for species of the *obscura* group. While crosses between the three most studied Nearctic species of the *obscura* subgroup gave interspecific hybrids, which made it possible to establish genetic homologies between the chromosomes of *D. pseudoobscura*, *persimilis*, and *miranda*, no results were obtained in extensive experiments with European species (Table 2). Hybrids were obtained, however, from the cross between species living on different continents: *D. ambigua* from Europe crossed with *D. pseudoobscura*, *persimilis*, and *miranda* from North America (Buzzati-Traverso and Scossiroli, 1952; Koske, 1952, 1953). Koske (1953) states that hybrid larvae were obtained from the crosses of *D. pseudoobscura* and *persimilis* with *D. tristis* and *bifasciata* but presented no data. The present authors have not been able to confirm this statement (Table 2). In the *affinis*

TABLE 2
Crosses Between Members of the *obscura* Group

Crosses female × male	*F₁ Hybrids*		*Gene exchange possible*	*References*
	♀♀	♂♂		
	obscura subgroup			
Nearctic members				
1. *pseudoobscura* × *persimilis*	Fertile	Sterile	Yes	Lancefield, 1929
2. *persimilis* × *pseudoobscura*	Fertile	Sterile	Yes	Lancefield, 1929
3. *pseudoobscura* × *miranda*	Fertile	Sterile	Yes	Dobzhansky, 1935a, 1937
4. *miranda* × *pseudoobscura*	Fertile	Sterile	Yes	Dobzhansky, 1935a, 1937
5. *persimilis* × *miranda*	Fertile	Sterile	Yes	Dobzhansky, 1935a, 1937
6. *miranda* × *persimilis*	Fertile	Sterile	Yes	Dobzhansky, 1935a, 1937
Palaearctic members				
7. *subobscura* × *tristis*	No progeny		—	Buzzati-Traverso, 1941b
8. *tristis* × *subobscura*	No progeny		—	Buzzati-Traverso, 1941b
9. *subobscura* × *bifasciata*	No progeny		—	Buzzati-Traverso, 1941b
10. *bifasciata* × *subobscura*	No progeny		—	Buzzati-Traverso, 1941b
11. *subobscura* × *obscura*	No progeny		—	Buzzati-Traverso, 1941b
12. *obscura* × *subobscura*	No progeny		—	Buzzati-Traverso, 1941b
13. *subobscura* × *ambigua*	No progeny		—	Buzzati-Traverso, 1941b
14. *ambigua* × *subobscura*	No progeny		—	Buzzati-Traverso, 1941b
15. *tristis* × *bifasciata*	No progeny		—	Buzzati-Traverso, 1941b
16. *bifasciata* × *tristis*	No progeny		—	Buzzati-Traverso, 1941b
17. *tristis* × *obscura*	No progeny		—	Buzzati-Traverso, 1941b
18. *obscura* × *tristis*	No progeny		—	Buzzati-Traverso, 1941b
19. *tristis* × *ambigua*	No progeny		—	Buzzati-Traverso, 1941b
20. *ambigua* × *tristis*	No progeny		—	Buzzati-Traverso, 1941b
21. *bifasciata* × *obscura*	No progeny		—	Buzzati-Traverso, 1941b
22. *obscura* × *bifasciata*	No progeny		—	Buzzati-Traverso, 1941b
23. *bifasciata* × *ambigua*	No progeny		—	Buzzati-Traverso, 1941b
24. *ambigua* × *bifasciata*	No progeny		—	Buzzati-Traverso, 1941b
25. *ambigua* × *obscura*	No progeny		—	Buzzati-Traverso, 1941b
26. *obscura* × *ambigua*	No progeny		—	Buzzati-Traverso, 1941b
Palaearctic × Nearctic members				
1. *ambigua* × *miranda*	Only pupae		No	Buzzati-Traverso, 1951b, Buzzati-Traverso and Scossiroli, 1952

TABLE 2. (*Continued*)

Crosses *female* × *male*	*F₁ Hybrids*		*Gene exchange possible*	*References*
	♀♀	♂♂		
Palaearctic × Nearctic members				
2. *miranda* × *ambigua*	No progeny		—	Buzzati-Traverso, 1951b; Buzzati-Traverso and Scossiroli, 1952
3. *ambigua* × *pseudoobscura*	Only pupae		No	Buzzati-Traverso, 1951b; Buzzati-Traverso and Scossiroli, 1952; Koske, 1953
4. *pseudoobscura* × *ambigua*	No progeny		—	Buzzati-Traverso, 1951b; Buzzati-Traverso and Scossiroli, 1952
	Sterile	Sterile	No	Koske, 1953
5. *ambigua* × *persimilis*	Only pupae		No	Buzzati-Traverso, 1951b; Buzzati-Traverso and Scossiroli, 1952
	Sterile	Sterile	No	Koske, 1953
6. *persimilis* × *ambigua*	No progeny		No	Buzzati-Traverso, 1951b, Buzzati-Traverso, and Scossiroli, 1952
	Only pupae			Koske, 1953
7. *tristis* × *miranda*	No progeny		—	Buzzati-Traverso and Scossiroli, unpubl.
8. *miranda* × *tristis*	No progeny		—	Buzzati-Traverso and Scossiroli, unpubl.
9. *tristis* × *pseudoobscura*	No progeny		—	Buzzati-Traverso and Scossiroli, unpubl.
10. *pseudoobscura* × *tristis*	No progeny		—	Buzzati-Traverso and Scossiroli, unpubl.
	Only pupae		No	Koske, 1953
11. *tristis* × *persimilis*	No progeny		—	Buzzati-Traverso and Scossiroli, unpubl.
	Only pupae		No	Koske, 1953
12. *persimilis* × *tristis*	No progeny		—	Buzzati-Traverso and Scossiroli, unpubl.
13. *subobscura* × *miranda*	No progeny		—	Buzzati-Traverso and Scossiroli, unpubl.
14. *miranda* × *subobscura*	No progeny		—	Buzzati-Traverso and Scossiroli, unpubl.

TABLE 2. (*Continued*)

Crosses *female* × *male*	*F*₁ *Hybrids*		*Gene exchange possible*	*References*
	♀♀	♂♂		
Palaearctic × Nearctic members				
15. *subobscura* × *pseudoobscura*	No progeny		—	Buzzati-Traverso and Scossiroli, unpubl.
16. *pseudoobscura* × *subobscura*	No progeny		—	Buzzati-Traverso and Scossiroli, unpubl.; Rendel, 1943
17. *obscura* × *miranda*	No progeny		—	Buzzati-Traverso and Scossiroli, unpubl.
18. *miranda* × *obscura*	No progeny		—	Buzzati-Traverso and Scossiroli, unpubl.
19. *obscura* × *pseudoobscura*	No progeny		—	Buzzati-Traverso and Scossiroli, unpubl.
20. *pseudoobscura* × *obscura*	No progeny		—	Buzzati-Traverso and Scossiroli, unpubl.
21. *obscura* × *persimilis*	No progeny		—	Buzzati-Traverso and Scossiroli, unpubl.
22. *persimilis* × *obscura*	No progeny		—	Buzzati-Traverso and Scossiroli, unpubl.
23. *bifasciata* × *miranda*	No progeny		—	Buzzati-Traverso and Scossiroli, unpubl.
24. *miranda* × *bifasciata*	No progeny		—	Buzzati-Traverso and Scossiroli, unpubl.
25. *bifasciata* × *pseudoobscura*	No progeny		—	Buzzati-Traverso and Scossiroli, unpubl.
26. *pseudoobscura* × *bifasciata*	No progeny		—	Buzzati-Traverso and Scossiroli, unpubl.
27. *bifasciata* × *persimilis*	No progeny		—	Buzzati-Traverso and Scossiroli, unpubl.
28. *persimilis* × *bifasciata*	No progeny		—	Buzzati-Traverso and Scossiroli, unpubl.
	Only pupae		No	Koske, 1953
	affinis subgroup			
Nearctic members				
1. *athabasca* × *azteca*	Sterile	Sterile	No	Sturtevant and Dobzhansky, 1936
2. *azteca* × *athabasca*	Sterile	Sterile	No	Sturtevant and Dobzhansky, 1936
3. *affinis* × *athabasca*	Sterile	Sterile	No	Miller, 1941
4. *algonquin* × *athabasca*	Fertile	Sterile	Yes	Miller, 1941

TABLE 2. (*Continued*)

Crosses female × male	*F_1 Hybrids*		*Gene exchange possible*	*References*
	♀♀	♂♂		
Palaearctic × Nearctic Members				
1. *affinis* × *helvetica*	No progeny		—	Buzzati-Traverso, 1951c
2. *helvetica* × *affinis*	No progeny		—	Buzzati-Traverso and Scossiroli, unpubl.
3. *algonquin* × *helvetica*	No progeny		—	Buzzati-Traverso and Scossiroli, unpubl.
4. *helvetica* × *algonquin*	No progeny		—	Buzzati-Traverso and Scossiroli, unpubl.
5. *narragansett* × *helvetica*	No progeny		—	Buzzati-Traverso and Scossiroli, unpubl.
6. *helvetica* × *narragansett*	No progeny		—	Buzzati-Traverso and Scossiroli, unpubl.
7. *azteca* × *helvetica*	No progeny		—	Buzzati-Traverso and Scossiroli, unpubl.
8. *helvetica* × *azteca*	No progeny		—	Buzzati-Traverso and Scossiroli, unpubl.
9. *athabasca* × *helvetica*	No progeny		—	Buzzati-Traverso and Scossiroli, unpubl.
10. *helvetica* × *athabasca*	No progeny		—	Buzzati-Traverso and Scossiroli, unpubl.
Crosses between subgroups				
1. *pseudoobscura* × *helvetica*	No progeny		—	Buzzati-Traverso and Scossiroli, unpubl.
2. *helvetica* × *pseudoobscura*	No progeny		—	Buzzati-Traverso and Scossiroli, unpubl.
3. *persimilis* × *helvetica*	No progeny		—	Buzzati-Traverso and Scossiroli, unpubl.
4. *helvetica* × *persimilis*	No progeny		—	Buzzati-Traverso and Scossiroli, unpubl.
5. *miranda* × *helvetica*	No progeny		—	Buzzati-Traverso and Scossiroli, unpubl.
6. *helvetica* × *miranda*	No progeny		—	Buzzati-Traverso and Scossiroli, unpubl.
7. *obscura* × *affinis*	No progeny		—	Buzzati-Traverso and Scossiroli, unpubl.
8. *affinis* × *obscura*	No progeny		—	Buzzati-Traverso and Scossiroli, unpubl.

TABLE 2. (*Continued*)

Crosses female × male	*F_1 Hybrids* ♀♀	♂♂	*Gene exchange possible*	*References*
Crosses between subgroups				
9. *obscura* × *algonquin*	No progeny		—	Buzzati-Traverso and Scossiroli, unpubl.
10. *algonquin* × *obscura*	No progeny		—	Buzzati-Traverso and Scossiroli, unpubl.
11. *obscura* × *narragansett*	No progeny		—	Buzzati-Traverso and Scossiroli, unpubl.
12. *narragansett* × *obscura*	No progeny		—	Buzzati-Traverso and Scossiroli, unpubl.
13. *obscura* × *azteca*	No progeny		—	Buzzati-Traverso and Scossiroli, unpubl.
14. *azteca* × *obscura*	No progeny		—	Buzzati-Traverso and Scossiroli, unpubl.
15. *obscura* × *athabasca*	No progeny		—	Buzzati-Traverso and Scossiroli, unpubl.
16. *athabasca* × *obscura*	No progeny		—	Buzzati-Traverso and Scossiroli, unpubl.
17. *obscura* × *helvetica*	No progeny		—	Buzzati-Traverso and Scossiroli, unpubl.
18. *helvetica* × *obscura*	No progeny		—	Buzzati-Traverso and Scossiroli, unpubl.
19. *subobscura* × *affinis*	No progeny		—	Buzzati-Traverso and Scossiroli, unpubl.
20. *affinis* × *subobscura*	No progeny		—	Buzzati-Traverso and Scossiroli, unpubl.
21. *subobscura* × *algonquin*	No progeny		—	Buzzati-Traverso and Scossiroli, unpubl.
22. *algonquin* × *subobscura*	No progeny		—	Buzzati-Traverso and Scossiroli, unpubl.
23. *subobscura* × *narragansett*	No progeny		—	Buzzati-Traverso and Scossiroli, unpubl.
24. *narragansett* × *subobscura*	No progeny		—	Buzzati-Traverso and Scossiroli, unpubl.
25. *subobscura* × *azteca*	No progeny		—	Buzzati-Traverso and Scossiroli, unpubl.
26. *azteca* × *subobscura*	No progeny		—	Buzzati-Traverso and Scossiroli, unpubl.

TABLE 2. (*Continued*)

Crosses female × male	*F₁ Hybrids* ♀♀	♂♂	*Gene exchange possible*	*References*
Crosses between subgroups				
27. *subobscura* × *athabasca*	No progeny		—	Buzzati-Traverso and Scossiroli, unpubl.
28. *athabasca* × *subobscura*	No progeny		—	Buzzati-Traverso and Scossiroli, unpubl.
29. *subobscura* × *helvetica*	No progeny		—	Buzzati-Traverso and Scossiroli, unpubl.
30. *helvetica* × *subobscura*	No progeny		—	Buzzati-Traverso and Scossiroli, unpubl.
31. *bifasciata* × *affinis*	No progeny		—	Buzzati-Traverso and Scossiroli, unpubl.
32. *affinis* × *bifasciata*	No progeny		—	Buzzati-Traverso and Scossiroli, unpubl.
33. *bifasciata* × *algonquin*	No progeny		—	Buzzati-Traverso and Scossiroli, unpubl.
34. *algonquin* × *bifasciata*	No progeny		—	Buzzati-Traverso and Scossiroli, unpubl.
35. *bifasciata* × *narragansett*	No progeny		—	Buzzati-Traverso and Scossiroli, unpubl.
36. *narragansett* × *bifasciata*	No progeny		—	Buzzati-Traverso and Scossiroli, unpubl.
37. *bifasciata* × *azteca*	No progeny		—	Buzzati-Traverso and Scossiroli, unpubl.
38. *azteca* × *bifasciata*	No progeny		—	Buzzati-Traverso and Scossiroli, unpubl.
39. *bifasciata* × *athabasca*	No progeny		—	Buzzati-Traverso and Scossiroli, unpubl.
40. *athabasca* × *bifasciata*	No progeny		—	Buzzati-Traverso and Scossiroli, unpubl.
41. *bifasciata* × *helvetica*	No progeny		—	Buzzati-Traverso and Scossiroli, unpubl.
42. *helvetica* × *bifasciata*	No progeny		—	Buzzati-Traverso and Scossiroli, unpubl.
43. *tristis* × *helvetica*	No progeny		—	Buzzati-Traverso and Scossiroli, unpubl.
44. *helvetica* × *tristis*	No progeny		—	Buzzati-Traverso and Scossiroli, unpubl.

TABLE 2. (*Continued*)

Crosses *female × male*	*F_1 Hybrids* ♀♀	♂♂	*Gene exchange possible*	*References*
Crosses between subgroups				
45. *affinis* × *tristis*	No progeny		—	Buzzati-Traverso and Scossiroli, unpubl.
46. *algonquin* × *tristis*	No progeny		—	Buzzati-Traverso and Scossiroli, unpubl.
47. *narragansett* × *tristis*	No progeny		—	Buzzati-Traverso and Scossiroli, unpubl.
48. *azteca* × *tristis*	No progeny		—	Buzzati-Traverso and Scossiroli, unpubl.
49. *athabasca* × *tristis*	No progeny		—	Buzzati-Traverso and Scossiroli, unpubl.
50. *ambigua* × *affinis*	No progeny		—	Buzzati-Traverso and Scossiroli, unpubl.
51. *affinis* × *ambigua*	No progeny		—	Buzzati-Traverso and Scossiroli, unpubl.
52. *ambigua* × *algonquin*	No progeny		—	Buzzati-Traverso and Scossiroli, unpubl.
53. *algonquin* × *ambigua*	No progeny		—	Buzzati-Traverso and Scossiroli, unpubl.
54. *ambigua* × *narragansett*	No progeny		—	Buzzati-Traverso and Scossiroli, unpubl.
55. *narragansett* × *ambigua*	No progeny		—	Buzzati-Traverso and Scossiroli, unpubl.
56. *ambigua* × *azteca*	No progeny		—	Buzzati-Traverso and Scossiroli, unpubl.
57. *azteca* × *ambigua*	No progeny		—	Buzzati-Traverso and Scossiroli, unpubl.
58. *ambigua* × *athabasca*	No progeny		—	Buzzati-Traverso and Scossiroli, unpubl.
59. *athabasca* × *ambigua*	No progeny		—	Buzzati-Traverso and Scossiroli, unpubl.
60. *ambigua* × *helvetica*	No progeny		—	Buzzati-Traverso and Scossiroli, unpubl.
61. *helvetica* × *ambigua*	No progeny		—	Buzzati-Traverso and Scossiroli, unpubl.

subgroup, interspecific crosses were successful only among some North American representatives.

The discovery that one Palaearctic species, which cannot be crossed with other representatives from the same region, gives hybrids when crossed with species from the Nearctic is of interest because it gives us a clue to the relationships between two geographically separated groups. The experimental evidence on this point, however, is partly controversial. The present authors found in 1950 that when *ambigua* females are crossed to any of the three mentioned North American species, a small number of hybrids are formed, some of which complete development and pupate but do not undergo metamorphosis; the reciprocal crosses did not give any result. Cytological studies of the hybrid larvae showed that in the salivary gland nuclei the chromosome strands of the parental species do not undergo synapsis, and therefore one can observe 13 free arms (5 of *pseudoobscura* and 8 of *ambigua*) originating from a common chromocenter in which the two small dot chromosomes (Figs. 9 and 10) can be seen. Koske (1953), on the other hand, using the same strains, reported that she obtained a few hybrid adults from one

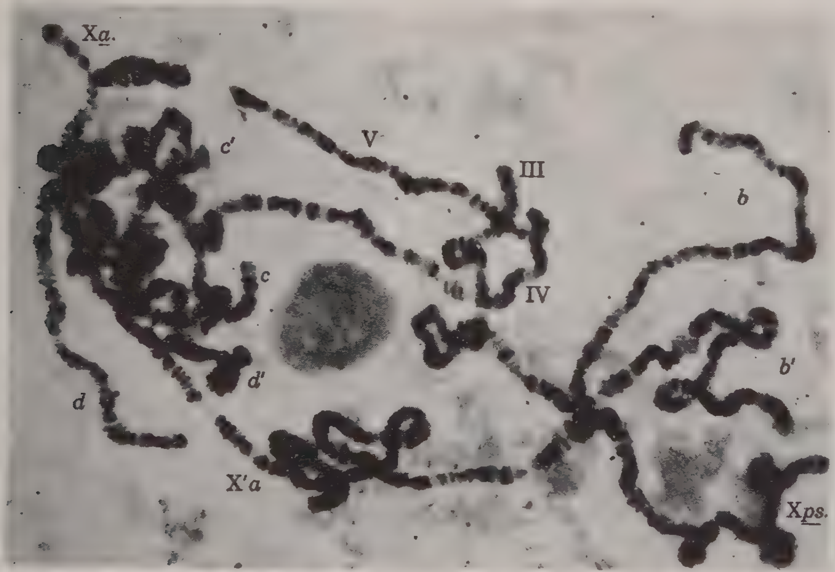

FIG. 9. Salivary gland chromosomes of hybrid larva from the cross: *D. ambigua* (Swiss strain) × *D. pseudoobscura* (Arrowhead gene arrangement, Aspen strain). *D. ambigua*'s chromosomes are indicated according to Frumento's terminology (Xa-X'a; b-b'; c-c'; d-d'); *D. pseudoobscura*'s chromosomes are indicated with Roman numbers, except for the X chromosome (Xps).

cross of *ambigua* ♀ × *persimilis* ♂, and from one of *pseudoobscura* ♀ × *ambigua* ♂. Furthermore, she observed salivary glands pairing between both *pseudoobscura* and *persimilis* chromosomes and those of *ambigua*. Such results would make it possible to ascertain homologies between cytological elements of the American and European species. Miss Koske kindly communicated her results to us and we made extensive but futile attempts to repeat them. In view of the interest of such observations,

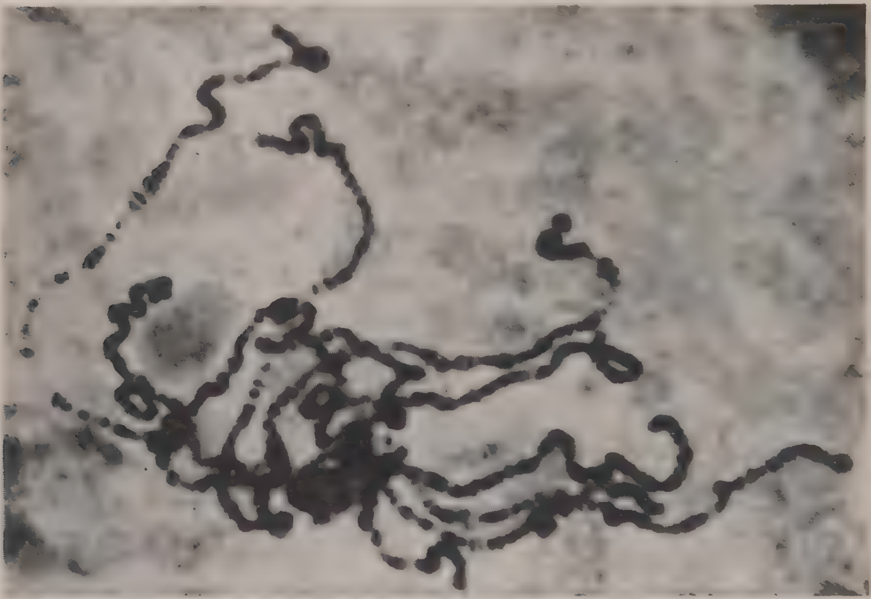

FIG. 10. Salivary gland chromosomes of hybrid larva from the cross: *D. ambigua* (Swiss strain) × *D. pseudoobscura* (Oaxaca strain). The 13 long arms of the parental species are well distinguishable.

extensive attempts were carried out to analyse further this phenomenon. Unfortunately, however, the results were completely negative.

In the course of these investigations, it turned out that the percentage of eggs which hatch to give larvae differs when different strains of both species are crossed (Table 3). This observation led to a further checking on this point.

Culture bottles with a minimum of 15 virgin *ambigua* females and 25 *pseudoobscura* (or *persimilis*, or *miranda*) males were set up and the number of pupae obtained during a period of 20 days was recorded. Four replications were made for each cross (Buzzati-Traverso and Scossiroli, 1952; Scossiroli, 1951, 1954). Table 4 gives the results of a first series of tests. It appears that the Chiricahua gene arrangement of *D. pseudo-*

obscura may be more successful in producing hybrid pupae than any of the other gene arrangements tested. If so, this might depend upon (1) a specific effect of the Chiricahua gene arrangement, or (2) a nonspecific effect due to the whole genotype. In order to test which of these assumptions was correct, a second series of tests was carried out, taking advantage of special strains constructed by Dr. Donald F. Mitchell for his experiments on the selective value of third chromosome types of *D. pseudoobscura*. Chiricahua and Standard third chromosome gene arrangements derived from Keen Camp and Pinon Flat, respectively, had been combined with the other chromosomes from Mather (Epling, Mitchell, and Mattoni, 1953).

TABLE 3

Percentage of Hatched Eggs and Pupae Recovered from Eggs Laid by *D. ambigua* (Swiss Strain) Females Kept with *D. pseudoobscura*, *D. persimilis*, and *D. miranda* Males

♂♂	*No. of eggs tested*	*Percent of eggs hatched*	*Percent of pupae recovered*
pseudoobscura Pinon, Standard g.a.	10,230	0.078	0.059
pseudoobscura Pinon, Arrowhead g.a.	10,084	0.323	0.188
pseudoobscura Aspen, Arrowhead g.a.	10,204	0.020	0.020
pseudoobscura Amecameca	10,077	0.050	0.030
pseudoobscura Tree Line, Morelia g.a.	10,106	0.059	0.020
pseudoobscura Pinon, Chiricahua g.a.	10,127	0.188	0.128
persimilis Sequoia, Standard g.a.	10,000	0.090	0.070
persimilis Porcupine, Arrowhead g.a.	10,009	0.070	0.030
persimilis Hope, Klamath g.a.	10,000	0.030	0.010
miranda Big Basin	10,100	0.0	0.0

The results shown in Table 5 (Scossiroli, 1954) indicate further that the Chiricahua chromosome type has a specific effect in the production of interspecific hybrid pupae. At the same time, comparison of the percentage of successful crosses in which geographically different *ambigua* strains were used shows that the southern European strains used were more successful than the Scottish ones.

Several dozen larvae derived from crosses using several geographic strains of both parental species have been studied cytologically. Not a single case of pairing was found. The fact that the hybrid larvae are somewhat larger than those of either parental species, and the remarkable thickness of the salivary chromosomes, raised the suspicion that the

TABLE 4

Tests of Fertility of Crosses between Strains of *D. ambigua* (Females) and *D. pseudoobscura*, *persimilis*, and *miranda* (Males)

	Strains of *D. ambigua* (♀♀)											
	Swiss		Terminillo		Admont		Dalkeith		Renfrew		Bonnyrigg	
Strains and gene arrangements (g.a.) of the male parents	*a**	*b*†	*a**	*b*†	*a**	*b*†	*a**	*b*†	*a**	*b*†	*a**	*b*†
g.a. Klamath:												
persimilis, Hope	4/20	0.18	4/6	0.47	4/6	0.37	4/28	0.22	4/28	0.18	4/28	0.08
g.a. Standard:												
persimilis Sequoia	6/7	1.20	6/7	1.20	6/7	0.90	5/28	0.27	11/28	0.37	2/28	0.05
pseudoobscura Pinon	17/21	0.78	11/16	0.51	4/6	0.50	2/28	0.03	2/28	0.03	5/28	0.10
g.a. Arrowhead:												
pseudoobscura Aspen	18/26	0.82	4/6	2.27	5/6	1.07	6/28	0.13	13/28	0.28	8/28	0.20
pseudoobscura Pinon	11/19	1.21	8/8	0.52	4/5	0.57	0/28	0	3/28	0.05	2/28	0.05
g.a. Chiricahua:												
pseudoobscura Pinon	15/21	1.99	3/6	0.97	5/6	1.72	7/28	0.27	3/28	0	2/28	0.03
g.a. Tree Line:												
pseudoobscura Morelia	5/15	0.12	4/9	0.17	—	—	0/28	0	0/28	0	0/28	0
miranda Big Basin	0/15	0	0/15	0	3/6	0.52	2/28	0.02	3/28	0.08	0/28	0

* In columns *a*, the number of cultures with larva are given against the total number of culture started.

† In columns *b*, the number of pupa per parental females are given.

TABLE 5

Tests of Fertility of Crosses between Strains of *D. ambigua* (Females) and Strains of *D. pseudoobscura* (Males) Differing in the Gene Arrangements of Their Third Chromosomes*

	No. of ♀♀	*No. of cultures*	*No. of fertile cultures*	*No. of pupae*	*No. of pupae per female*
D. ambigua Dalkeith × *D. pseudoobscura*					
Keen Camp, g.a. Chiricahua, strain 304	60	28	7	12	0.20
Keen Camp, g.a. Chiricahua, strain 311	60	28	4	2	0.03
Keen Camp, g.a. Standard, strain 265	60	28	1	1	0.02
Keen Camp, g.a. Standard, strain 313	60	28	4	8	0.13
Pinon Flat, g.a. Chiricahua, strain 325	60	28	2	2	0.03
Pinon Flat, g.a. Chiricahua, strain 344	60	28	1	0	0.0
Pinon Flat, g.a. Standard, strain 284	60	28	1	0	0.0
Pinon Flat, g.a. Standard, strain 337	60	28	1	1	0.02
D. ambigua Swiss strain × *D. pseudoobscura*					
Keen Camp, g.a. Chiricahua, strain 304	60	28	10	52	0.87
Keen Camp, g.a. Chiricahua, strain 311	60	28	11	66	1.10
Keen Camp, g.a. Standard, strain 265	60	28	7	10	0.17
Keen Camp, g.a. Standard, strain 313	60	28	6	15	0.25
Pinon Flat, g.a. Chiricahua, strain 325	60	28	8	12	0.20
Pinon Flat, g.a. Chiricahua, strain 344	60	28	6	11	0.18
Pinon Flat, g.a. Standard, strain 284	60	28	7	26	0.43
Pinon Flat, g.a. Standard, strain 337	60	28	4	10	0.17
D. ambigua Admont × *D. pseudoobscura*					
Keen Camp, g.a. Chiricahua, strain 304	60	28	14	27	0.45
Keen Camp, g.a. Chiricahua, strain 311	60	28	7	15	0.25
Keen Camp, g.a. Standard, strain 265	60	28	6	21	0.35
Keen Camp, g.a. Standard, strain 313	60	28	6	15	0.25
Pinon Flat, g.a. Chiricahua, strain 325	60	28	8	4	0.07
Pinon Flat, g.a. Chiricahua, strain 344	60	28	7	7	0.12
Pinon Flat, g.a. Standard, strain 325	60	28	6	11	0.18
Pinon Flat, g.a. Standard, strain 337	60	28	8	14	0.23
D. ambigua Terminillo × *D. pseudoobscura*					
Keen Camp, g.a. Chiricahua, strain 304	60	28	12	41	0.68

TABLE 5. (*Continued*)

	No. of ♀♀	*No. of cultures*	*No. of fertile cultures*	*No. of pupae*	*No. of pupae per female*
D. ambigua Terminillo × *D. pseudoobscura*					
Keen Camp, g.a. Standard, strain 265	45	21	7	11	0.24
Keen Camp, g.a. Standard, strain 313	60	28	7	22	0.37
Pinon Flat, g.a. Chiricahua, strain 325	15	7	3	9	0.60
Pinon Flat, g.a. Chiricahua, strain 344	60	28	6	8	0.13
Pinon Flat, g.a. Standard, strain 284	30	14	2	2	0.06
Pinon Flat, g.a. Standard, strain 337	60	28	12	15	0.25

* Strain numbers as from C. Epling.

larvae were allopolyploids. This possibility was carefully checked by ascertaining whether any of the thirteen threads would show occasional unpaired regions and thus indicate diploid condition. No such case was found; furthermore, counts of mitotic metaphase plates in the hybrids do not seem to support this possibility.

In spite of the fact that it has not been possible to confirm Koske's results, they certainly are very interesting because they indicate that, on rare occasions, one may obtain hybrids between species which ordinarily cannot cross. Koske's proposed homologies between *pseudoobscura* and *ambigua* chromosomes, however, appear doubtful, especially with respect to the X chromosome. While there is a good correspondence in the relative length of the salivary gland chromosomes of *D. pseudoobscura* and *subobscura*, it turns out that the X chromosome of *ambigua* is about 20 units shorter than that of *pseudoobscura* (see Table 9). Similar, although less striking, discrepancies are to be found in the comparison of the remaining elements. Koske's diagram of cytologic homologies fails to account for these differences.

The results reviewed above indicate that, in the material examined, genetic divergence between species living in different zoogeographic regions has reached a point where (1) only a very small fraction of the produced hybrid zygotes undergoes development; (2) development of those hybrid zygotes that complete the embryonic stages is bound to come to a standstill during larval life, or at the latest during metamorphosis, probably as a consequence of the lack of pairing between somatic chromosomes; (3) only exceptional environmental circumstances allow chromosome pairing to take place and this is accompanied by complete ontogenesis.

TABLE 6
Homologies between Chromosomes of Species of the *obscura* Group and *D. melanogaster*

Species	*Chromosome Elements*						*Reference*
	A	B	C	D	E	F	
melanogaster	X	2L	2R	3L	3R	4	Muller, 1940
pseudoobscura	XL	4	3	XR	2	5	Lancefield, 1922
persimilis	XL	4	3	XR	2	5	Tan, 1935b
miranda	XL	4	X2	XR	2	5	Dobzhansky and Tan, 1936
affinis	XL	4	3	XR	2	5	Sturtevant, 1940
algonquin	XS	C	A	XL	B	D	Miller, 1939
azteca	XS	C	A	XL	B	D	Dobzhansky and Sokolov, 1939
athabasca	A	B	C	D	E	F	Novitski, 1946
subobscura	X	III	IV	II	V	VI	Dept. of Biometry, University College, London, 1936–54
subobscura	X	II	V	III	IV	VI	Frizzi, 1950
subobscura	A	E	U	J	O	D	Mainx, Koske, and Smital, 1953

VII. Relationships

With the possible exception of *D. seguyi*, whose inclusion in this group of species is doubtful, the *obscura* group has a typical Holarctic distribution. Both subgroups, *affinis* and *obscura*, are represented in the Old and the New Worlds, but the degree of differentiation they have undergone is remarkably different. Eight species belonging to the *affinis* subgroup are present in the Nearctic, while only one occurs in the Palaearctic; and, on the contrary, the four Nearctic forms of the *obscura* subgroup are matched by six described and probably more than two undescribed forms in the Palaearctic. The degree of ecologic valence of the two subgroups is very different in the two continents, too. While the distribution range of the *affinis* subgroup covers practically the whole North American continent, the *obscura* subgroup is represented by its various forms only west of the Rocky Mountains, and only one species, *D. pseudoobscura*, is widespread over a vast area and occupies ecologically different biotopes. On the Eurasian continent, on the other hand, the only species of the *affinis* subgroup, *D. helvetica*, has a very patchy distribution and seems to have rather restricted ecological requirements. The species of the *obscura* subgroup, on the contrary, occur all over the vast area comprised between the Atlantic and the Pacific Oceans, with four species, *D. bifasciata, alpina, subobscura,* and *obscura* distributed over very wide ranges, both in terms of geography and ecology. It appears that the *obscura* group has undergone a different type of evolution in the Palaearctic and in the

Nearctic. In the Palaearctic, the *obscura* subgroup has undergone a greater differentiation, producing a larger number of species capable of varied ecological adjustments, whereas the *affinis* subgroup has not produced many forms and remained ecologically restricted. In the Nearctic, an opposite tendency is evident; the *affinis* subgroup has evolved more species and thereby occupied a vaster area than the *obscura* subgroup. Such different evolutionary patterns of the two subgroups in the Holarctic regions, as revealed at the taxonomic level, are reflected in the morphology, the behavior, the cytology, and probably in the genetic systems of the species.

TABLE 7

Numbers of Characters in Common between Any Two Given Species of the *obscura* Subgroup. 48 Morphological Traits Have Been Considered

Species	*obscura*	*tristis*	*bifasciata*	*ambigua*	*subobscura*	*persimilis*	*pseudoobscura*	*miranda*
obscura	—	25	27	24	17	13	16	14
tristis	25	—	19	26	21	14	17	13
bifasciata	27	19	—	17	21	12	12	13
ambigua	24	26	17	—	23	13	15	13
subobscura	17	21	21	23	—	13	12	11
persimilis	13	14	12	13	13	—	37	36
pseudoobscura	16	17	12	15	12	37	—	40
miranda	14	13	13	13	11	36	40	—

Considering the morphology of the species belonging to the *obscura* subgroup first, we notice that the amount of differentiation in the three well-known North American species is very little (Reed and Reed, 1948), so little, in fact, that the two species *pseudoobscura* and *persimilis* were considered as physiological races of the same species for several years. The five Eurasian species can be distinguished more easily from one another, especially in the male sex. Only old males of *D. obscura* and *D. bifasciata* would usually be confused, but *D. tristis* and *D. obscura* females are practically indistinguishable. The degree of similarity between species can be directly evaluated in Table 7 where the number of morphological traits in common between any two species are given. Only those species are noted for which at least 48 morphological traits could be considered. It can be concluded that *D. subobscura* differs more from each of the members of the Eurasian subgroup than the latter differ from each other, but, at the same time, its differences with *D. obscura* and *D. bifasciata* are of a different sort than those with *D. ambigua* and *D. tristis*. These conclusions are in good agreement with the data presented by Weidman (1951) and Spieth (1952) concerning the mating behavior of these forms. A superficial comparison of the Eurasian with the American forms could lead one to believe that *D. obscura* and especially *D. bifasciata* are closer in their morphology to *D. pseudoobscura* than to other Palaearctic forms. As Table 7 shows, however, this is not the case; the morphological similarity is distinctly greater within forms of one continent than between forms of two continents. *D. ambigua*, as previously mentioned, can be crossed with *D. pseudoobscura, persimilis*, and *miranda;* its similarity to the American forms is, however, not greater than that of other European species. On the basis of Table 7 classification, in fact, *D. obscura* and *tristis* have a larger number of traits in common with the Nearctic forms.

TABLE 8

Numbers of Characters in Common between Any Two Given Species of the *affinis* Subgroup. 38 Morphological Traits Have Been Considered

Species	*algonquin*	*affinis*	*athabasca*	*azteca*	*narragansett*	*tolteca*	*helvetica*
algonquin	—	27	28	23	24	14	19
affinis	27	—	27	22	26	13	16
athabasca	28	27	—	25	27	15	22
azteca	23	22	25	—	24	17	24
narragansett	24	26	27	24	—	12	23
tolteca	14	13	15	17	12	—	12
helvetica	19	16	22	24	23	12	—

A similar table for the morphological comparison between the species of the *affinis* subgroup has been constructed (Table 8), taking into account 38 characters. Here it appears that *D. algonquin, affinis, athabasca, azteca*, and *narragansett* form a very homogeneous group, and this is well in agreement with the results of hybridization experiments. No data of this type are available for *narragansett*, but the morphology of this species with a limited geographic distribution does not depart appreciably from the others just mentioned. *D. tolteca*, the sixth Nearctic species, on the other hand, has a unique position with respect to the other five; in fact it deviates more than *D. helvetica*, the only representative of the subgroup in the Palaearctic. The latter, however, as shown in Table 2, does not produce any hybrid with the Nearctic relatives.

Summarizing the evidence derived from morphological comparisons it can be said that: (1) subgroups differ from one another more than species of the same subgroup belonging to different zoogeographical regions; (2) in the *obscura* subgroup species have diverged more between than within zoogeographical regions, and are represented by one complex (*pseudoobscura-persimilis-miranda*) in the Nearctic, two complexes (*obscura-bifasciata* and *ambigua-tristis*) and one widespread, abundant species (*subobscura*) in the Palaearctic; (3) in the *affinis* subgroup species have diverged to the same extent if not more, within rather than between zoogeographical regions, and are represented by one complex (*algonquin-affinis-athabasca-azteca-narragansett*) in the Nearctic, and two outstanding species, one in the Nearctic (*tolteca*) and one in the Palaearctic (*helvetica*).

Chromosome evolution within the *obscura* group has certainly been conspicuously greater than in other species groups. The cytological configuration with five rods and a dot, i.e., six separate chromosome elements, regarded as basic for the genus Drosophila (Muller, 1940; Sturtevant and Novitski, 1941; Patterson and Stone, 1952) is found in *D. subobscura.* The karyotypes of other species of the group have probably been derived either by fusions or by pericentric inversions. Homologies between the chromosome elements of *D. melanogaster* and of this group have been established for several American and for just one European species (Table 6). The integrity of the five long elements has been retained in spite of changes in the number and shape of the chromosomes. A comparison of the relative lengths of the long elements in the salivary gland chromosomes (Table 9) supports this conclusion. This also seems to hold true for *D. subobscura,* in spite of the appreciable amount of intercalary heterochromatin present. Similar data are presented in the lower part of Table 9 for some of the species for which chromosome homologies have not yet been established. (We consider *ambigua* in this group, since the homologies proposed by Koske do not seem convincing, as pointed out in Section IV.) The configuration of *D. alpina* is probably derived from three fusions, although it is not yet clear how the five basic elements have been repatterned to form the chromosome configurations of *D. ambigua, bifasciata, obscura,* and *tristis.* A more detailed study of the genetics and cytology of these species appears urgently needed for a complete understanding of the chromosome evolution within this species group.

A very interesting trait which appears typical of this group of species is the greater variability in the gene sequences presented by element C. As Novitski (1946) pointed out, the number of different gene arrangements found in element C of *D. pseudoobscura* and *persimilis* (Chromosome 3), as well as of *D. athabasca* (Chromosome C), *algonquin* (Chromosome A), and *azteca* (Chromosome A) is greater, or at least equal to that of any other chromosome. This trait is not limited to the Nearctic species, for Stumm-Zollinger (1953) found 11 different inversions in element C (Chromsome V) of *D. subobscura,* as contrasted with a maximum of 5 in the second most variable chromosome. The effect of the concentrating

TABLE 9

Relative Lengths of the Long Elements in the Salivary Glands Nuclei

Species	*Element* A	B	C	D	E	*References*
algonquin	16.4	18.5	19.7	20.0	25.4	Miller, 1939
azteca	15.1	18.8	19.0	21.4	25.8	Dobzhansky and Sokolov, 1939
pseudoobscura	14.0	19.9	16.3	24.0	25.8	Tan, 1937; Dobzhansky and Tan, 1936
subobscura	17.3	20.9	17.0	20.5	24.3	Frizzi, 1950
	16.5	20.4	18.1	20.1	24.9	Mainx *et al.*, 1953
	Terminology used and lengths					
obscura	A = X	E	I	O	U	Mainx *et al.*, 1953
	9.6 + 10.0	9.7 + 14.0	15.8 + 17.4	10.5	13.0	
	3 + 3	4 + 5	1 + 2	1'	2'	Prevosti, 1950
	16.4 + 10.4	13.4 + 9.3	15.9 + 14.7	11.0	8.9	
ambigua	A	E	I	U		Mainx *et al.*, 1953
	7.5 + 11.2	11.3 + 11.4	17.7 + 17.3	10.6 + 13.0		
	X	D	B	C		Frumento, 1954
	10.4 + 9.7	10.0 + 9.3	17.2 + 16.2	12.5 + 14.7		
tristis	1	2	3	4		Prevosti, 1950
	16.7 + 15.2	16.1 + 12.6	13.2 + 11.5	7.3 + 7.4		
bifasciata	1	2	3	4		Prevosti, 1950
	16.5 + 17.6	17.6 + 12.7	9.0 + 13.5	7.7 + 5.4		

of many gene sequences in one particular element and its significance for the evolution of the group is far from understood, especially since such inversions seem to perform different functions in different species. Thus, whereas in *D. pseudoobscura* seasonal variations in gene frequencies and the characteristic geographic distribution of certain inversions can be related to different adaptive values of the genetic material present in the various gene sequences (Dobzhansky, 1947, 1948, 1952; Heuts, 1948; Levine, 1952), in *D. subobscura* no seasonal cycles have been observed, no chromosomal geographic races have been identified, and no correlation has been found between the degree of chromosome polymorphism and the number of ecological niches available in any given locality. In *D. willistoni* and related species the greatest chromosome variability is found in element E (Dobzhansky, Burla, and Da Cunha, 1950), while in other widely distributed species, such as *D. melanogaster*, all the chromosome elements seem to be equally constant in their gene sequences. What factors are responsible for such marked differences in the genetic systems of various species, and what part they may have played in their evolution remains an open question, in spite of the great amount of work which has been aimed toward an understanding of the function of chromosome polymorphism in the Nearctic species. The fact that one particular chromosome element maintains a greater plasticity than any other throughout this species group and in different zoogeographical regions, points to the importance of the mechanism.

Finally, at the level of genetic variability, the *obscura* group provides us with a very fine example of how different ecological conditions can be met by different genetic systems. On one hand, we find species, such as *D. bifasciata* and *D. athabasca,* having an exceedingly wide longitudinal range of distribution, and also species showing the ability of withstanding a great variety of ecological conditions, such as *D. subobscura,* found in the Lebanon desert and in the highlands of Scotland, and *D. pseudoobscura* found in tropical Mexico and in the mountain forests of British Columbia. On the other hand, we have highly specialized entities such as *D. tristis,* found only in the neighborhood of rivers or springs, or *D. seminole,* which seems limited only to a small area in Alabama. Accordingly, we find temperature races, chromosomal polymorphism as well as an impressive amount of genetic heterogeneity in wild populations, and various genetic mechanisms, all developed to cope with a variety of environments.

The various lines of evidence which we have discussed indicate that the evolutionary history of this group of species has been very varied. Faced with the problem of conquering an increasingly wider range of habitats, the hypothetical ancestor of this group of species has given origin to a remarkable series of variations on the same theme. At some times, isolating mechanisms were established and accordingly new taxonomic entities were born, at other times a large genetic diversification took place within the previously existing specific limits. The presence of the two subgroups in both the Palaearctic and the Nearctic, together with the fact that differences within subgroups are smaller than between subgroups, even when comparing species living in different zoogeographical regions, point to an ancient origin of the two subgroups and of the whole complex of species. The evidence derived from cytological data is well in agreement with this view.

We could now attempt a reconstruction of the phylogenetic history of the *obscura* group, but we regard the data at our disposal as being too vague to justify any such attempt, except in particular cases such as that of the *D. pseudoobscura* complex of sibling species, mentioned above. We have been able to bring together enough information to show close taxonomic relationships and genetic affinities among the described species, and it has been possible to identify some common cytologic denominators in the evolution of the group. We are bound to assume that the genetic changes leading to the present conditions have taken place over a long period of time. Unfortunately, no known fossil records are available of the progenitors of the now living *Drosophila obscura* and, therefore, we should, in our attempt, rely exclusively on speculation. Sturtevant (1940) pointed out that probably *D. pinicola* is the most primitive living member of the genus and that the *obscura* group, being the closest to this species, could possibly be the most primitive species group. In view of the fact that we can base our conclusions only on those forms which are now living, and that we have no way of telling which may have disappeared in the past, we accept Sturtevant's conclusion but prefer not to construct a phylogeny of the species within the *obscura* group.

The history of the studies on the Drosophilae of the *obscura* group and the results obtained, which we have attempted to summarize and discuss, are the best proof of the fact that, even when they do not lead to a well constructed phylogenetic tree, investigations of this sort are very important for a better understanding of evolutionary mechanisms. As it always happens in science, a deeper knowledge opens wider horizons and brings out new, previously unsuspected problems. The study of evolutionary mechanisms within the *obscura* group is far from being exhausted; the data here collected indicate the directions along which further work will be likely to produce important information and make the origin of this group less obscure.

VIII. ACKNOWLEDGMENTS

The authors are indebted to numerous persons to whom they wish to express their appreciation of help received. They are under obligation first of all to Mr. Giordano Peschiera for assistance over a period of many years with collections of specimens in nature, maintenance of stocks, and help in the course of experiments. They are grateful to the Department of Biometry, University College, London, and particularly to Dr. Helen Spurway-Haldane for communicating unpublished observations and for having made available many strains; they are likewise indebted to Prof. Felix Mainx, Vienna, Austria, and to Prof. Daigoro Moriwaki, Tokyo, Japan. We wish to express our appreciation to Prof. K. Anders, University of Lund, Sweden, for the collection of living specimens of *D. obscura* in its *terra typica*. Strains have been received from Mr. E. B. Basden, Edinburgh, Scotland; Prof. Th. Dobzhansky, New York, N.Y.; Prof. C. Epling, Los Angeles, California; Prof. E. Hadorn, Zürich, Switzerland; Professor D. D. Miller, Lincoln, Nebraska; Prof. J. T. Patterson, Austin, Texas; Dr. A. Prevosti, Barcelona, Spain; thanks are due to all these colleagues. The authors are indebted to Prof. Carl Epling for a critical reading of the manuscript and for numerous helpful comments.

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Särtryck ur Tellus nr 2, 1955

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Distribution of Radioactivity in Pelagic Clays[1]

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(Manuscript received September 14, 1954; revised January 29, 1955.)

Abstract

An attempt is made to study the localization of radioelements in different mineral phases of pelagic clay sediments. The results so far obtained indicate that the ionium supported radium is redistributed by diffusion through the interstitial solution and that the authigenic zeolite phillipsite plays an important role as a scavenger of radioelements within the deposit. The mechanism of transfer of radioelements from the ocean to pelagic deposits is discussed, and points of uncertainty in the interpretation of the distribution of gross beta-activity are indicated.

The distribution of radioelements in marine sediments has been extensively studied, primarily for use as a geochronological tool. However, serious shortcomings in dating pelagic sediments have arisen in the cases where uranium and its daughter products have been utilized (a summary of the present situation is given by Kröll, 1954). Much of the difficulty in the interpretation of the distribution of uranium, ionium and radium in pelagic sediments stems from a lack of knowledge of the chemical behavior of these elements in marine waters as well as in the sediments.

The purpose of the present investigation was to obtain a deeper insight into the chemistry of the natural radioactive elements in marine deposits through the study of the radioactivity in different components of the pelagic clays.

Experimental

The gross beta-activity of clay samples was determined with a windowless flow counter (Nuclear Instrument and Chemical Model

Table 1. Pelagic sediment samples used for the investigation

Sample	Expedition	Core	Latitude	Longitude	Depth	Description
A	Capricorn	33 BG	12° 46′ S	143° 33′ W	4375 m	Mixed material mainly from the lower part of the 128 cm core
B	»	49 BP	9° 17′ N	124° 09′ W	4400	0—24 cm
C	»	21—25 HG + 33 BG	16.5°—17° S	159°—163° W	4375—5150	Mixed material
D	»	31 BG	17° 29′ S	158° 40′ W	4900	4—12 cm
E	»	31 BG	17° 29′ S	158° 40′ W	4900	Mixed material
F	Yo—Yo	7 P	20° 50′ N	125° 11′ W	4520	0—30 cm
	Capricorn	23 HG	16° 59′ S	161° 35′ W	5150	Entire core. Each sample integrating vertically over 4 cm
G	»	39 BG	15° 02′ S	113° 49′ W	2940	Top 4 cm

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[1] Contribution of the Scripps Institution of Oceanography, New Series No. 789. This work represents results of research conducted by the University of California under contract with the Office of Naval Research (Contract Nonr-233 (17).

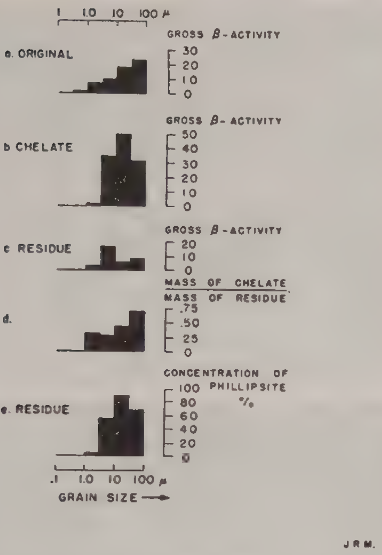

Fig. 1. Distribution of properties in sample A.

D-46 A), in the Geiger region. The powdered sample was compressed into an aluminum planchet with a diameter of 3.1 cm and a depth of 0.2 cm giving 0.1—0.2 g of solid per cm² of sample surface. For small samples equally deep planchets were employed with diameters of 1.5 and 1.0 cm and the corresponding net count was multiplied by the appropriate surface factors. The gross beta-activity is mainly due to the decay products of radium and to a minor extent to UX, potassium-40 (about 3 counts per minute), and beta emitters of the thorium family. Loss of emanation would thus markedly influence the results.

The gross beta-activity of the different size fractions of a ferruginous pelagic clay from the South Pacific (Sample A, see Table 1) demonstrated that the coarse fractions are considerably more active han the fine fractions (Fig. 1a and table 2). Since the zeolite phillipsite displayed a similar size distribution (figure 1e), it appeared possible that the activity was associated with this mineral.

To check this assumption, phillipsite in mixed material from the cores *Capricorn 21—25 HG* and *33 BG* was isolated from other minerals by repeated centrifugation of the grains larger than 80 μ in an ethylene tetrabromide-diethyl phthalate mixture with a density of 2.16. The lighter fraction consisted entirely of phillipsite, mostly in the form of single lathes. An intermediate fraction of density 2.16—2.28 contained approximately 95 % of this mineral in the form of crossed twins and spherolithic aggregates, approximately 3 % of manganese micronodules and the rest fossil fragments and unidentified minerals. The heavy fraction with a density greater than 2.50, constituting about 40 % of the size fraction used, consisted mainly of manganese micronodules, with subordinate amounts of feldspar, quartz, phosphatic fossil fragments, fish teeth, foraminiferal tests and 6 % phillipsite. The net activity of the light, intermediate and heavy fractions were 32, 42 and 16 counts per minute respectively.

Radioautographs were prepared of the light (pure phillipsite) and the heavy (phillipsite-poor) fraction by spraying a thin coating of lacquer over a glass slide, distributing the grains over the sticky surface and coating them with another thin spray of lacquer. After drying the specimens, a piece of Eastman No-Screen X-ray film was brought in contact with the mount and exposed for seven weeks. In the light fraction all grains (439) were active enough to give an autograph. In the heavy fraction 130 out of 3,200 grains or 4 % of the sample produced darkening of the film. This is in reasonable agreement with the phillipsite content of 6 %.

Additional autographs were prepared by evaporating suspensions of the light and the heavy fraction of sample D on glass slides, covering the mounts with Kodak liquid

Table 2. β-activity of the size fractions of sample A.

Size Fraction μ	Net β-activity counts/minute	Wt % of total sample	Concentration of phillipsite %
> 32	23.7	6,5	63
10—32	18.9	9.2	89
3.2—10	10.3	12.3	51
1.0—3.2	5.6	22	4
< 1.0	1.8	50	not measured

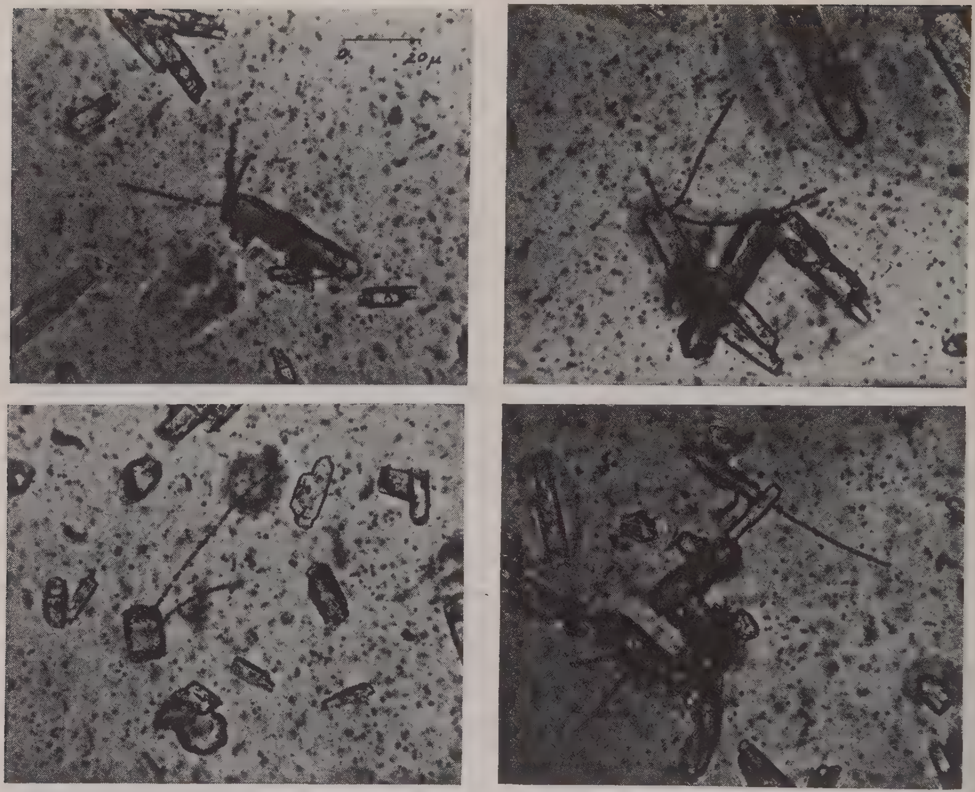

Fig. 2. Radioautographs of alpha particles emitted from phillipsite crystals (sample D) embedded in nuclear track emulsion.

nuclar track emulsion, drying, and exposing for ten days.

Out of 886 phillipsite crystals counted, twenty-five displayed alpha tracks, whereof eight single, nine double, and seven three-branched tracks. In one case eight tracks emerged from one single phillipsite crystal. Microphotographs of some of the active crystals are shown in Fig. 2.

As only the upper side of the mount was coated with emulsion, the recording geometry is approximately 50 %. Most of the single and double tracks observed may therefore be expected to correspond to three-branched stars with one or two of the alpha particles emitted into the glass slide. The high proportion of three-branched stars indicates that the activity is mainly due to an intercept of a disintegration series containing two short-lived alpha emitters. This leaves as the only possibility radium, radon and radium A as the elements responsible. As only in one case a two-branched star was observed in the emulsion without connection to a mineral grain it is probable that the phillipsite retains the emanation in an efficient way.

In the heavy (phillipsite-poor fraction) mounted and exposed in the same way as the light fraction, only three mineral grains out of 3,640 counted, displayed alpha tracks, confirming that the radium of the grain size fraction above 5 μ is practically entirely bound to phillipsite.

Most of the activity could be removed by chelation for ½ hour at 100° C. with the neutral ammonium salt of ethylene diamine tetra-acetic acid (Figures 1b – c and Table 3) and by cation exchange using 1N ammonium

Table 3. Chelation of β-active components in sample A.

Size fraction μ	Net β-activity, counts/min	
	Chelate, ashed	Residue
> 32	—	8.2
10—32	30.9	4.7
3.2—10	49.3	14.1
1—3.2	34.4	3.5
< 1	1.5	—

acetate (Table 4). The active constituent occurring in the phillipsite is therefore believed to be sorbed in the pores of the zeolite structure.

The salt from the interstitial solution generally displays a low beta activity which can partly be accounted for by potassium-40 (approx. 3 counts/min). An exception is the interstitial salt from the highly active surface layer of core *Capricorn 31 BG* (Sample D, Table 4 and 5), possibly indicating that in this case a considerable fraction of the radioactive elements are dissolved and not yet in sorption equilibrium with the solid phases.

Sample D displays the highest gross beta activity found in any material so far investigated by the present authors. In contrast to the conditions in the samples A and C, the almost phillipsite-free (4 %) clay fraction displays the same high activity as the pure phillipsite fraction (> 5 μ, $\varrho < 2.25$) (Table 5).

In order to test the correlation between the stratigraphically abnormal activity and the concentration of phillipsite in the sedimentary sequence, a core was selected (*Capricorn 23 HG*) which displayed in the upper part the type of activity distribution, expected as a result of decay, and in the lower part a marked secondary activity maximum (Fig. 3). All samples from this sequence were analyzed for their phillipsite concentration, using the intensity above background of the X-ray radiation diffracted by planes with the spacing $d_{hkl} = 3.175$ Å. A North American Philips Norelco X-ray diffractometer was used, employing Mn-filtered Fe Kα radiation. The intensities were measured by the time required to accumulate 3,200 counts (40—180 seconds) and the experimental error is approximately ± 3 % of the concentration. The results, shown in Figure 3 indicate that the stratum 44—68 cm, carrying an abnormally high activity, is also characterized by a high content of phillipsite.

Table 4. Net β-activity of salt from interstitial solution, and of sorbed ions exchanged with 1N ammonium acetate.

Sample	Net β-activity counts/min.
B salt.........	4.2
B sorbate......	67
D salt.........	65
E salt.........	6.5
E sorbate......	126
F salt.........	9.4
F sorbate......	34

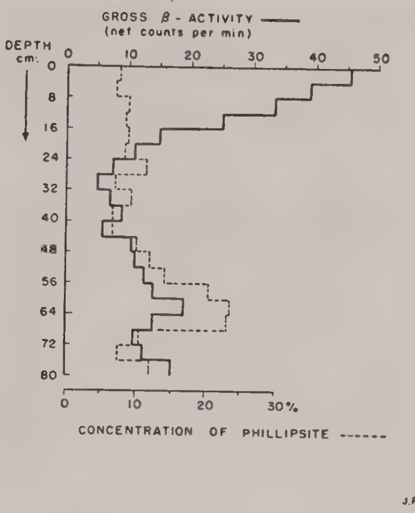

Fig. 3. Vertical distribution of gross beta-activity and phillipsite in core *Capricorn 23 HG*.

The above related results can be summarized in the following way: The beta-active con-

Table 5. Net β-activity of sample D.

Size fraction μ	Density fraction	Net β-activity counts/min.	Phillipsite conc. %
< 5	—	86	4
> 5	< 2.25	89	100
> 5	> 2.25	36	17

stituents are to a great extent sorbed by phillipsite both in the younger and older strata. The fraction of the deposit which is finer than $5\,\mu$, and which largely consists of clay and hydroxide minerals, is highly beta active in the young sediment, but displays a low activity in the lower parts of the sequence, where significant amounts of unsupported ionium can be expected to be absent. In one case a high beta-activity has been observed in the interstitial salt from the top stratum of the sediment.

The alpha-activity has so far been investigated only in the grain size fraction $> 5\,\mu$ of the young sediment, and is in this to a large extent due to radium and its daughter elements radon and radium A, all bound practically entirely to phillipsite.

Discussion

To explain the distribution of the radioelements observed in marine sediments, the solid matter that accumulated or contained these elements, as well as the chemical reactivity of these elements in the sediments merit consideration (KURBATOV, 1936).

The *lithogenous* (GOLDBERG, 1954) contribution of radioactivity appears generally to be relatively unimportant in the pelagic sediments of the Pacific. This is indicated by the fact (PETTERSSON, 1938; PIGGOT and URRY, 1941) that most of the ionium is not uranium supported.

The accumulation of ionic ionium and radium in hydrogenous oxide-, clay- and zeolite minerals appears to be the quantitatively most important mechanism of transfer of radioelements to the pelagic sediments of the Pacific Ocean. This accumulation could be explained by coprecipitation (scavenging) of the radioelements by the solid phases in statu nascendi, and isomorphous replacement under the same conditions. Scavenging of ionium with ferric hydroxide (PETTERSSON 1953) and with manganese oxides (GOLDBERG 1954) have been suggested. As a considerable fraction of the pelagic clay minerals may be precipitated from dissolved aluminum and silica in the ocean (ARRHENIUS 1954), aluminosilicates may also have to be taken into account as scavengers for radioelements in sea water. The contribution of radioelements by the accumulation of *biogenous* material in the sediments is apparently of less importance than the hydrogenous contribution. EVANS, KIP and MOBERG (1938) found that the shell material in a Pacific mud sample contained but a minor amount of the total radium content of the sediment. Further, core *Capricorn 39 BG*, which has a calcium carbonate content of circa 70 %, shows a beta-activity, based upon its $CaCO_3$-free weight, equivalent to that of the carbonate-free clays in adjacent pelagic areas.

An indication of the minimum contribution of biogenous unsupported radium is given by the radium and barium contents of sea water and pelagic clays, assuming that both elements have similar geochemical paths through the biosphere (*i.e.* fixation in the skeletons and in the soft parts of marine organisms). The barium content of some Pacific pelagic clays attains values of more than 1 % and there is evidence for a biogenous origin of more than 95 % of the barium (GOLDBERG and ARRHENIUS, unpublished). The Ba/Ra ratio in sea water cannot be defined exactly inasmuch as only an upper limit for the Ba-concentration is known. Using the values of $\mathrm{Ra} = 3 \cdot 10^{-11}$ mg/l and $\mathrm{Ba} < 9 \cdot 10^{-2}$ mg/l, the ratio is $< 3 \cdot 10^{-9}$ and the expected concentration of biogenous, unsupported radium in sediments is $3 \cdot 10^{-12}$ g/g or greater. Since the concentration of Ra in the upper strata of the sediment is between 10 and 70×10^{-12} g/g, the Ba-concentration of sea water needs to be only a few times less than the reported upper limit to make biogenous Ra important as a possible guest element in marine organisms.

Attempts are made at the present time to investigate in detail the distribution of radioelements in stratigraphically surveyed pelagic sediment sequences. On the basis of the present results, and of previous work by HAHOFER and HECHT, KOCZY, KRÖLL, KURBATOV, PETTERSSON, PICCIOTTO and WILGAIN, PIGGOT and URRY, it appears most likely that the high activity of the clay- and hydroxide-mineral fraction at the present sediment surface is largely due to ionium-supported radium.

The abnormal activity of the old strata, originally observed by PETTERSSON (1953), KRÖLL (1954), BARANOV and KUZMINA (1954), may in some cases be due to displaced radium, sorbed by phillipsite from the interstitial solution. Other possibilities, which have to be investigated, are that the activity maxima in old strata are due to presence of excess uranium (as indicated by some of the results of HAHOFER and HECHT, 1954), high concentration of potassium, or to a high retension of radon in the phillipsite, as compared to other minerals present.

The authors are indebted to Dr E. Picciotto for helpful criticism and valuable suggestions.

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PRINTED IN SWEDEN
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Reprinted from JOURNAL OF BACTERIOLOGY
Vol. 70, No. 5, pp. 568–571, November, 1955
Printed in U.S.A.

A SURVEY OF THE PIGMENTS OF A NUMBER OF CHROMOGENIC MARINE BACTERIA, WITH SPECIAL REFERENCE TO THE CAROTENOIDS

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Received for publication April 15, 1955

More than half the bacteria occurring in the sea are chromogenic. In a general survey of several thousand colonies isolated from marine sources ZoBell and Feltham (1934) found that 31.3 per cent were yellow, 15.2 per cent orange, 9.9 per cent brown and 5.4 per cent red or pink. Later, ZoBell and Upham (1944) described 60 new marine species 19 of which were yellow, 5 brown, 5 pink or salmon colored, 4 orange and one red. Many species of bacteria which spoil fish are also chromogenic and the general information on this subject has been summarized by ZoBell (1946). In spite of the easy availability of this material, only one investigation (Hodgkiss *et al.*, 1954) has so far been published on the nature of the pigments of marine bacteria. Two primary isolates from the skin slime of *Gadus morrhuae*, A1032 and A1062, which are coryneform, both synthesize the carotenoids, neoxanthin, sarcinaxanthin and corynexanthin but in different relative amounts. A1062, but not A1032, also produces coproporphyrin under certain cultural conditions. The present paper reports a general survey on the nature of the pigments in a number of species isolated by Dr. ZoBell and his collaborators.

EXPERIMENTAL METHODS

Cultural methods. The medium used throughout consisted of peptone, 5.0 g; yeast extract (Difco), 1.0 g; $FePO_4$, 0.1 g; glucose 1.0 g; and 75 per cent sea water, 1000 ml; the pH of the medium was adjusted to 7.6; sterilization was obtained by autoclaving. Cultures were grown in mass (300 to 350 ml of medium) in either Roux bottles or Fernbach flasks at 25 C for as long as was necessary for heavy growth and pigmentation to occur. The cells were harvested by centrifuging in a Servall G/1 angle centrifuge and then decanting the supernatant. For pressure studies cultures were grown in specially constructed leucite tubes holding approximately 200 ml of medium. After inoculation with a heavy suspension in order to obtain maximal growth, the cells were incubated in pressure cylinders (ZoBell and Oppenheimer, 1950) for 8 days. The pressures used were the highest which the species under examination could tolerate (Oppenheimer and ZoBell, 1952).

The species examined included those previously described by ZoBell and Upham (1944) together with a number of as yet unclassified isolates contributed by C. H. Oppenheimer, D. E. Contois and H. L. Scotten.

Extraction and identification of the pigments. The pigments were extracted by grinding the wet centrifuged cells with ethanol and, if necessary, warming. An extraction procedure often used for micro-organisms involves first grinding the cells to a fine dry powder with anhydrous Na_2SO_4, prior to treatment with ethyl ether (Garton, Goodwin and Lijinsky, 1951); this method could not be used with most of the bacteria examined here. As observed by Hodgkiss *et al.* (1954), with their marine bacteria, the pigments cannot be extracted from the dry mass, either because they are so tightly adsorbed to the Na_2SO_4 or because the pigment-protein complex, the state in which the pigments exist naturally, is not broken down by this treatment. The latter explanation is probably correct, for in the present experiments it was obvious that the various species differed considerably in the ease with which they yielded their pigments to ethanol. The critical factor always appeared to be the ease with which the cell proteins coagulated; immediately the proteins were denatured, the pigment was liberated into the ethanol.

The ethanol extract was freed from cellular debris by centrifuging, and an equal volume of ethyl ether or light petroleum (b.p. 30 to 60 C) was added, followed by water dropwise until two layers formed. The upper layer was removed and taken to dryness at 40 C in a stream of illuminating gas. The residue was treated in one of two ways: (a) dissolved in a small volume (5 ml) of

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light petroleum (or, if insoluble, in a few drops of ethyl ether followed by dilution to 5 ml with light petroleum) ready for chromatography; (b) saponified by heating to boiling for 2 min with 5 ml of ethanolic KOH (20 per cent, w/v); the unsaponifiable fraction, containing the pigments, was extracted and prepared for chromatography as described by Goodwin and Morton (1946).

Chromatography of the extracts was carried out either on columns of alumina (Merck-Brockmann) deactivated according to the method of Goodwin and Srisukh (1949) or on $CaCO_3$ (analytical grade).

The pigments were identified by the position and shape of their absorption spectra and by their relative positions on a chromatogram.

Absorption spectra were measured using either a Beckman DU or Unicam SP600 instrument.

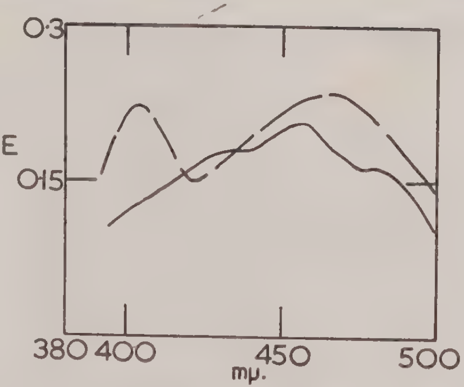

Figure 1. The absorption spectra in light petroleum (b.p. 30–60 C) of the pigment extract from *Micrococcus aquivivus.* Before saponification, - - - - -. After saponification, ———.

RESULTS

Micrococcus species. Micrococcus aquivivus, M. maripuniceus and *M. infimus* yield a pigment mixture to ethanol only with difficulty. On saponifying the extract one of the components (λ_{max} 404 mμ) is destroyed leaving a carotenoid (figure 1) in the unsaponifiable fraction. This pigment is completely hypophasic when partitioned between light petroleum and 90 per cent aqueous methanol. It is unstable, disappearing from a $CaCO_3$ column during development of the chromatogram, while it is so tightly absorbed that it cannot be eluted from alumina even with glacial acetic acid. It is almost certainly a polyhydroxy carotenoid which, because of the large difference in the position of its absorption maximum in ethanol and light petroleum solutions, probably also contains a carbonyl group. It cannot be identified with any previously described pigment. It differs from the pigments in the only other *Micrococcus* spp. recently examined, *M. luteus* and *M. flavus* (Sobin and Stahly, 1942).

The nature of the material with a band at 404 mμ is unknown, but it appeared in many of the bacteria examined during this investigation. The amount produced also varies in different cultures of the same bacterium. *M. sedentarius* produced no detectable amounts of carotenoids under our conditions.

Flavobacterium species. Flavobacterium marinotypicum yielded a bright yellow ethanol extract which when chromatographed separated into two fractions with the same absorption spectrum ($\lambda\lambda_{max}$ 418, 439, 468) as neoxanthin, sarcinaxanthin and corynexanthin. Both fractions are epiphasic in the partition test and one (A) is absorbed about as strongly as lycopene and the other (B) as a monohydroxy carotenoid. From these properties *A* is almost certainly sarcinene first observed in *Sarcina lutea* by Chargaff & Dieryjck (1932) and *B* sarcinaxanthin first isolated from the same source. Sarcinene has previously been observed in *F. sulphureum* by Sobin & Stahly (1942).

F. okeanokoites and *F. marinovirosum* give easily extractable yellow extracts with absorption bands having maxima around 410 mμ. This pigment is destroyed by saponification and is therefore not a carotenoid.

Pseudomonas species. Pseudomonas xanthochrus and *P. aestumarina* produce two carotenoids *A* and *B* which, from their absorptive behavior, are a mono- and a dihydroxy carotenoid respectively. Their absorption spectra are identical with those of cryptoxanthin and zeaxanthin, and it is almost certain that *A* and *B* are these pigments. Figure 2 shows the absorption spectrum of *A* compared with that of authentic cryptoxanthin (Goodwin, 1954) (the spectra of cryptoxanthin and zeaxanthin are virtually indistinguishable).

Vibrio species. Vibrio adaptatus synthesizes the same pigments as *P. xanthochrus*, i. e., cryptoxanthin and zeaxanthin. Other *Vibrio* species examined, *V. hyphalus, V. phytoplanktis* and *V. marinofulvus*, produced no carotenoids. *V. algosus* is unique among the marine bacteria examined in producing two carotenoids containing different chromophoric systems. Figure 2 shows the ab-

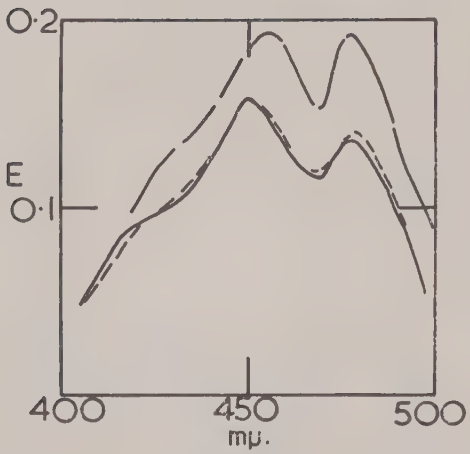

Figure 2. The absorption spectra in light petroleum (b.p. 30–60 C) of: Pigment A from *Pseudomonas xanthochrous*, ———. Authentic cryptoxanthin, - - - - -. Pigment A from *Vibrio algosus*, —— —— ——.

sorption spectra of pigment *A*, which appears to be a carotenoid with about the same absorbability as lycopene. Pigment *B* is probably a dihydroxy carotenoid with its main absorption spectral maxima at 450 mμ. Its full spectrum has not been recorded because of the difficulty of obtaining it in a pure state.

Serratia marinorubra. The purple pigment in this organism was easily extracted from the bacteria mass with ethanol. In acidified ethyl ether it is purplish-pink, and in alkaline ether yellowish-brown; the absorption spectra of these two forms were identical with those of prodigiosin (Hubbard and Rimington, 1950) (λ_{max} 470 mμ in alkali and 536 mμ in acid). Furthermore, the isosbestic point for the two forms of the pigment was the same as for prodigiosin (495 mμ). These facts combined with the partition behavior of the pigment, which is also identical with that of prodigiosin, make it certain that it is prodigiosin.

Undescribed species. The following bacteria, which have not yet been identified, were examined for carotenoids (the numbers are reference numbers in the Scripps collection):

623: Produces small amounts of a pigment very similar to that produced by *M. aquivivus.*

7 C: A single strongly absorbed carotenoid is produced with a symmetrical absorption spectrum with a maximum at 468 mμ in ethanol (figure 2). The lack of fine structure suggests that it is a ketocarotenoid. It is not acidic.

102-6-3: Produces a strongly absorbed yellow pigment (λ_{max} 418, 441, 472 mμ in ethanol) with a spectrum identical with that of the sarcinene-sarcinoxanthin, corynexanthin group. Its absorptive behavior suggests that the pigment is corynexanthin.

9 B and 102-8-FB: Produce the two pigments found in *P. xanthochrus* and *P. aestumarina*—probably cryptoxanthin and zeaxanthin.

102-8-F: Produces a pigment very similar to that of *M. aquivivus.*

The following bacteria, not discussed above, were slightly yellow, but produced no significant amounts of carotenoids under our experimental conditions: *Actinomyces halotrichis*, *P. coenobios*, *P. obscura*, *P. oceanica*, *P. perfectomarinus*, and *Sarcina pelagia.*

Effect of pressure. The following marine bacteria were cultured under the pressure indicated. *F. marinotypicum*, 200 atmos; *M. aquivivus*, 400 atmos; and *P. xanthochrus*, 100 atmos. These bacteria were chosen because they produced different carotenoids. In every case the pigments produced under pressure were the same as those produced under normal conditions.

DISCUSSION

The carotenoids produced by chromogenic marine bacteria do not appear to differ greatly from those produced by other bacteria. The main general characteristics in each case are (a) comparative lack of hydrocarbon carotenoids, (b) synthesis of polyhydroxy compounds, and (c) failure to synthesize lutein, the characteristic xanthophyll of the higher plants.

It is not possible to attach any far-reaching taxonomic importance from the present limited survey or even to suggest that a wider study would demonstrate this importance, but the following should be noted: (a) the pigments of *M. aquivivus*, *M. maripuniceus* and *M. infimus* have not been observed in other genera; (b) the cryptoxanthin and zeaxanthinlike pigments occur in members of the genera *Vibrio* and *Pseudomonas*; and (c) the pigments in *F. marinotypicum* are those normally also found in some chromogenic *Corynebacterium* and *Sacina* sp.

ACKNOWLEDGMENTS

We wish to thank Drs. C. E. ZoBell and D. L. Fox for their help and encouragement during this investigation. One of us (T. W. G.) is grateful to The University of California and The Rockefeller Foundation for financial assistance.

SUMMARY

A survey of a number of chromogenic marine bacteria indicates that the pigments present are generally carotenoids. Polyhydroxyxanthophylls predominate and carotenes are rarely observed. This picture is also characteristic of non-marine bacteria.

The pigment in *Serratia marinorubra* is prodigiosin.

High pressure has no effect on the synthesis of carotenoids by marine bacteria.

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SEDIMENT ZONES BORDERING THE BARRIER ISLANDS OF CENTRAL TEXAS COAST

BY

FRANCIS P. SHEPARD AND DAVID G. MOORE

Reprinted from
Finding Ancient Shorelines
A Publication of the Society of Economic Paleontologists and Mineralogists
a Division of
The American Association of Petroleum Geologists

SEDIMENT ZONES BORDERING THE BARRIER ISLANDS OF CENTRAL TEXAS COAST[1]

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ABSTRACT

An investigation of the Recent sediments along the Texas coast has been centered around Rockport and Aransas Pass. Fifteen different environments of deposition have been defined in the bays, on the barrier islands and on the open continental shelf. Methods have been devised by which investigators can ordinarily classify into the correct environment of deposition test samples from the Texas coastal area. A variety of techniques is used in distinguishing the environments, a particularly effective system being based on estimation with a binocular microscope of the general composition of sieved sizes of the sand fraction of sediments. The grain-size characteristics of the sediments offer important supplementary information on the environments. The contained organisms, especially the Foraminifera, provide valuable independent evidence in finding the nature of the site of deposition. It seems likely that environments in ancient sediments like those now existing along the Texas coast could be distinguished by similar methods, making it possible to find the direction of the sand masses constituting ancient barrier islands by determining the environment of deposition of sediment from core samples and outcrops.

Among the diagnostic characteristics are the following: (1) approaches to the barrier islands are indicated by rapid increases in the sand content; (2) the muddy sediments of the bays differ from the muddy sediments of the open shelf by the appreciable glauconite and echinoid content of the latter; (3) the nearness to an entering river can often be determined by the high plant fiber content, by lamination, and by high ratios of Ostracoda to Foraminifera; (4) the inner shelf deposits (inside about 20 fathoms) lack the abundant planktonic Foraminifera which characterize the outer shelf and both the total Foraminifera and shells increase in the outer shelf deposits. All of these characteristics apply to the central Texas coast area, probably apply also to most of the western Gulf coast, and possibly have a general application to all similar environments.

INTRODUCTION

Traditionally the shore and nearshore areas are the zones where coarse-grained sediments are deposited. Hence, the interest in "finding the shoreline." Along most of the Texas coast, however, the shoreline of the mainland has only intermittent and narrow sand fringes and is bordered by relatively broad bays or lagoons which contain predominantly fine-grained deposits. The principal sand deposits are found on or near the barrier islands. These sandy islands have widths up to about five miles and represent deposition of sand concurrent with that of the fine sediments in the bays and on the continental shelves seaward of the islands. As a result, in studying ancient sediments of similar environments the important zone for pervious sediments is not the mainland beaches but the barrier islands which may be many miles seaward of the mainland coast.

The Rockport area (fig. 1), 30 miles north of Corpus Christi, was chosen as one of two principal field areas in the sedimentation project supported by the American Petroleum Institute because it represented typical conditions of bays,

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[1] Contribution from the Scripps Institution of Oceanography, New Series No. 791. This investigation was supported by a grant from the American Petroleum Institute, Project 51. The writers wish to express their appreciation for the important contribution made to this study by D. M. Poole and the information and suggestions supplied by the project steering committee and by numerous staff members of Scripps Institution. The field work was aided by the Texas Game and Fish Commission and the U. S. Fish and Wildlife Service.

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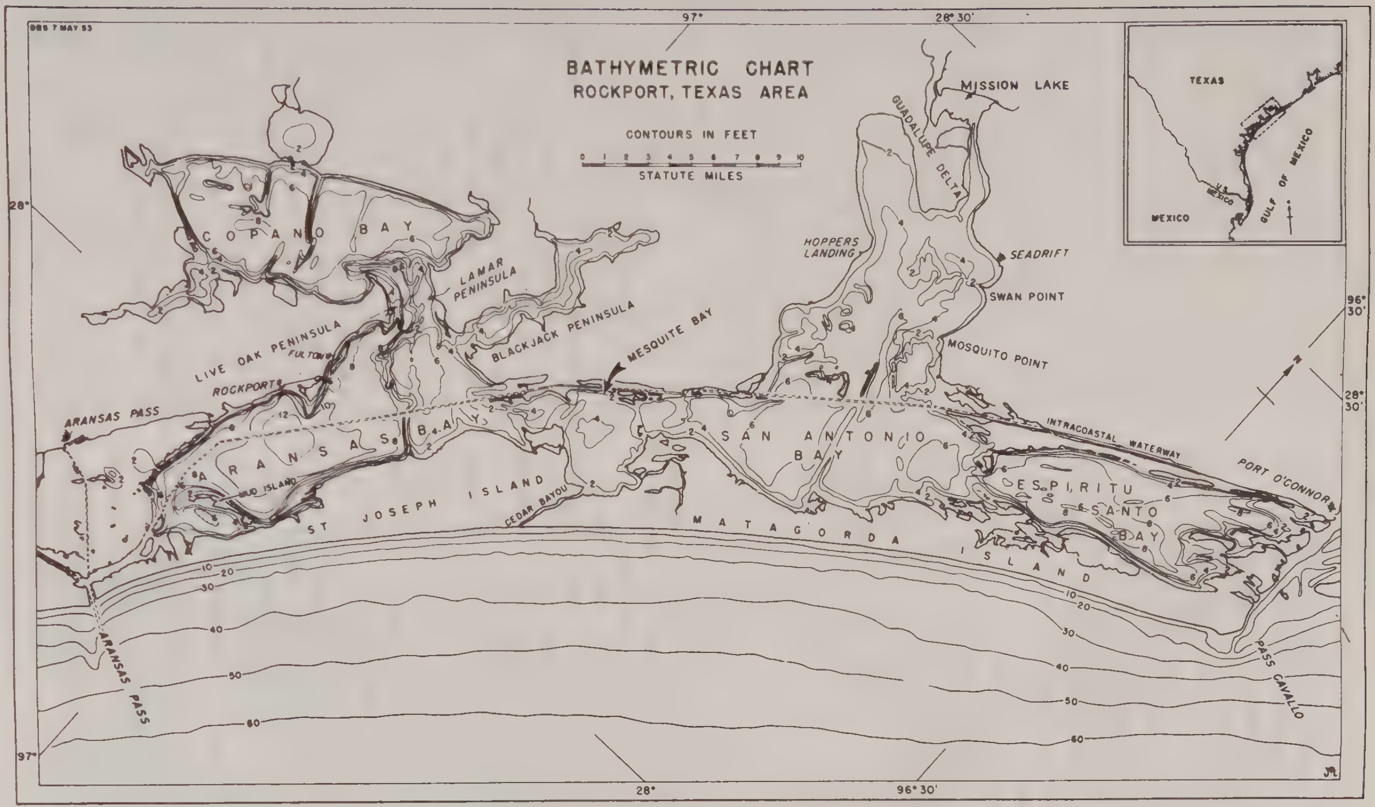
BATHYMETRIC CHART
ROCKPORT, TEXAS AREA
CONTOURS IN FEET
0 1 2 3 4 5 6 7 8 9 10
STATUTE MILES
97°
28° 30'
28°
96° 30'
MISSION LAKE
GUADALUPE DELTA
HOPPERS LANDING
SEADRIFT
SWAN POINT
MOSQUITO POINT
TEXAS
MEXICO
U.S. MEXICO
GULF OF MEXICO
COPANO BAY
LAMAR PENINSULA
BLACKJACK PENINSULA
MESQUITE BAY
LIVE OAK PENINSULA
FULTON
ROCKPORT
ARANSAS PASS
ARANSAS BAY
MUD ISLAND
ST JOSEPH ISLAND
CEDAR BAYOU
SAN ANTONIO BAY
MATAGORDA ISLAND
ESPIRITU SANTO BAY
INTRACOASTAL WATERWAY
PORT O'CONNOR
PASS CAVALLO
ARANSAS PASS
10
20
30
40
50
60
N
DBS 7 MAY 53

FIG. 1.—Depths of the bays and inner shelf in an area along the central Texas coast (see inset for location). Note that the contour interval in the bays is two feet, and ten feet on the open shelf.

barrier islands, and open shelf and because the bays had not been polluted to any great extent by industries. The existence of two marine laboratories in the area gave additional advantages. One of the larger rivers of Texas enters San Antonio Bay and has built an extensive delta into the bay head. All of the bays have oyster reefs although they are particularly abundant in Copano Bay. Mesquite and lower Aransas Bays are influenced by inlets. A large part of Aransas Bay is relatively free from all of these influences and has deeper water than the other bays. The barrier islands have broad beaches, dune tracts, and low marshy flats on the side towards the bays. The continental shelf extends seaward for about 50 miles and is a fairly typical shelf for sedimentation studies. Thus the area has an interesting diversity of environments.

METHODS OF DESCRIBING ENVIRONMENTS

An extensive literature is available describing various methods of sediment analysis. Recent attempts to apply these methods to determine environments of deposition have shown some inadequacies. As a result, refinements of earlier techniques and development of entirely new methods have been found necessary in these environmental studies.

In distinguishing between sediments formed in different depositional environments along the Texas coast, the writers have devised a simple but effective system.[2] This is based on an examination under binocular microscopes of the coarse fraction (greater than 1/16 mm) sieved to the Wentworth size grades.[3] Estimates are made of the percentages of significant constituents[4] such as echinoids, Foraminifera, glauconite, ostracods, mollusk shells, plant fibres, and terrigenous (land-derived minerals of which quartz is dominant in this area). Other groups are used where they seem to be significant. The estimate of percentage by volume of each of these items is plotted for each screen size. Using the weights of the screenings, the volume estimates of the various materials are computed as percent by weight of the total sample[5] and the results plotted in a "pie" diagram which shows also the total content of the undifferentiated silt and clay. Figure 4 gives these two types of diagrams as the averaged results of the analyses of sediments from the various environments. The graph at the top contains the average frequency polygon for the sand-size fractions in each environment. These averages are actually close to the majority of samples in each environment, so that most samples can be distinguished as to environment by the three types of plotting.

Another method which has been used to characterize the sediments is presented in the accompanying paper by Inman and Chamberlain. This makes use of the particle-size distribution employing various statistical measures. A third system is based on a triangular plot of the sand, silt, and clay ratios obtained from the grain-size analyses (fig. 4).

Organisms found in the sediments are also diagnostic of the general conditions at times of deposition, serving as a means of distinguishing between the following environments: (1) upper bay where there is low salinity due to fresh water from streams; (2) lower bay where there is mixing of the fresh water with the salt water entering through the inlets; (3) marshes and inlets of the inner barrier islands; and (4) offshore continental shelf types. The Foraminifera have been studied extensively and the general assemblage is found to be closely related to the environments.[6] Macroorganism assemblages are closely related to these same environments and can be used wherever there are sufficient numbers of these organisms in the sediment to provide a characteristic faunal assemblage. Environmental influences, particularly salinity, have been indicated by study of: (1) ostracods, (2) clay minerals, and (3) ratios of the chemical make-up of the sediments (indicated by spectrochemical analyses made for us recently by the California Research Corporation).

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[2] The system is described in more detail elsewhere (see Shepard and Moore, 1954).

[3] Ordinarily included are material over 1 mm, 1 to ½ mm, ½ to ¼ mm, ¼ to ⅛ mm, and ⅛ to 1/16 mm.

[4] Two observers working independently are used to obtain these estimates.

[5] Volume and weight are roughly comparable in most of the sediments from the Texas coast area.

This paper is concerned principally with the description of sediments deposited under different environmental conditions as indicated by coarse fraction studies under the binoculars and by the sand-silt-clay ratios. Other methods of characterizing the same environments will be described in forthcoming reports by co-workers on API Project 51.

SEDIMENTATION IN THE BAYS

Description and Processes

The bays of the Texas coast include: (1) elongate lagoons inside of and parallel to the barrier islands, and (2) estuaries which extend into the coast at right angles to the general trend of the shore line. Both of these types are well represented in the Rockport area where most studies have been made. Figure 1 gives the general bathymetry of the bays. It will be noted that Aransas Bay attains the greatest depths, somewhat over 12 feet, whereas Copano and San Antonio Bays are shallower with maximum depths of seven and eight feet respectively. Mesquite and St. Charles Bays do not have depths over about four feet. In general the steep slopes occur along the shore and the floors of the bays are flat. The topography of the bays is, however, considerably influenced by oyster reefs which rise as shoals in Copano Bay and as both shoals and small islands in portions of Aransas and San Antonio Bays.

The bays receive a considerable supply of fresh water from the Guadalupe River (171,000 acre feet between 1941 and 1951; Texas 1952), and much smaller supplies from the Aransas and Mission Rivers which enter indirectly into Copano Bay. Salt water enters Aransas Bay through Aransas Pass, Mesquite Bay through Cedar Bayou, and San Antonio Bay through Espiritu Santo Bay indirectly from Pass Cavallo. During periods of low rainfall evaporation in the bays raises the chlorinity until locally it is even higher than that of the open ocean (fig. 2A). Ordinarily, however, the chlorinity is considerably lower than the ocean and is particularly low near the Guadalupe River (fig. 2B).

Here as elsewhere the final sediment which is incorporated in the stratigraphic column is the resultant of the processes of sediment deposition and sediment removal by resuspension and current action. In these shallow bays each storm produces waves which are competent to resuspend some of the sediment deposited during previous quiet periods. Wind velocities, combined with depth and size of the bays, control the effectiveness of waves. Thus deep bays and portions of the bays sheltered from the strongest winds are less affected by waves. Wind-induced currents are particularly effective in the narrow restricted parts of the bays where they produce a concentrated flow which is somewhat sustained in adjacent portions of the bays. Tidal currents are of little importance in the bays because of the small tidal range. In areas adjacent to portions of the barrier islands, wind transport especially of the dune sand may be of importance. All of these factors tend to control the composition of the sediment.

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[6] The Foraminifera of the San Antonio Bay area near Rockport have been described (see Parker, et al, 1953).

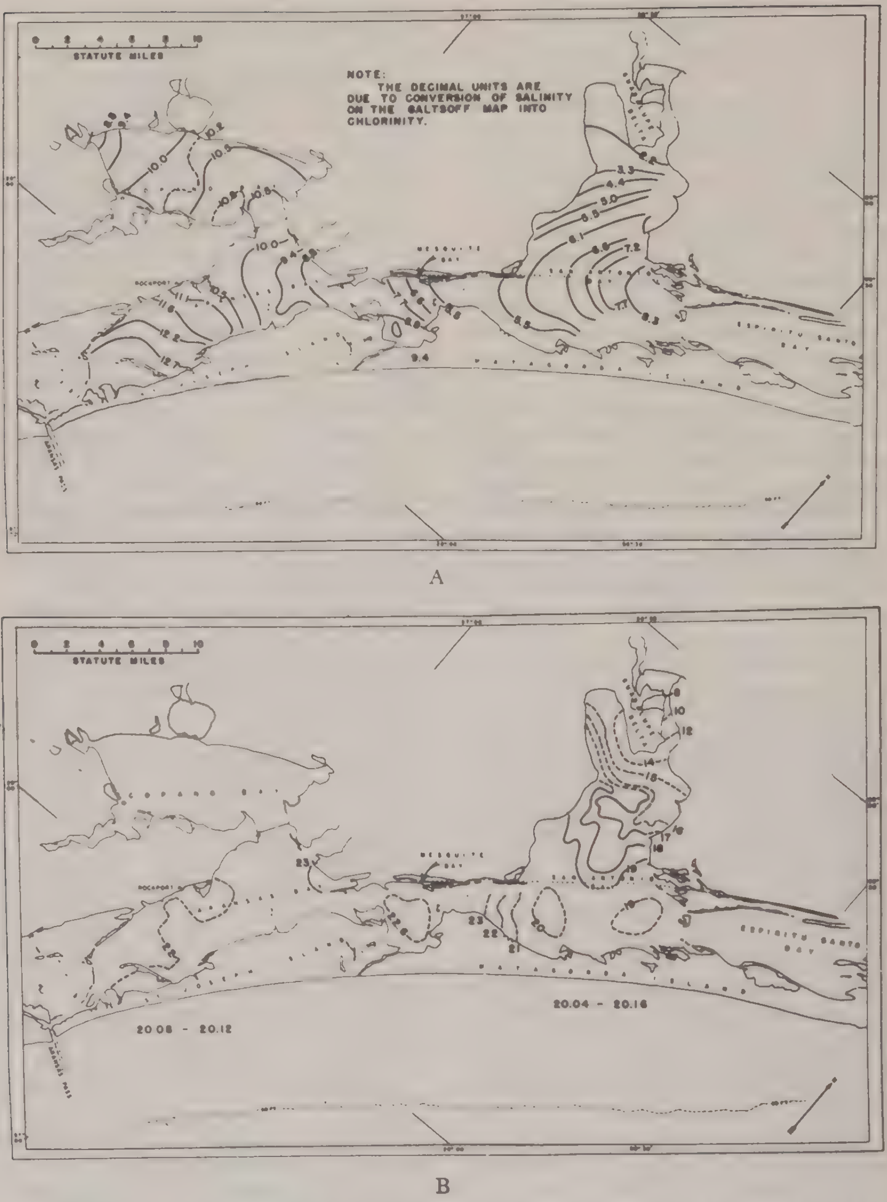
STATUTE MILES
NOTE:
THE DECIMAL UNITS ARE DUE TO CONVERSION OF SALINITY ON THE SALTSOFF MAP INTO CHLORINITY.
MESQUITE BAY
ROCKPORT
ESPIRITU SANTO BAY
MATAGORDA ISLAND
A
STATUTE MILES
COPANO BAY
MESQUITE BAY
ROCKPORT
ESPIRITU SANTO BAY
MATAGORDA ISLAND
20.08 - 20.12
20.04 - 20.16
B

Fig. 2.—Chlorinity in the bays of the Rockport area under conditions of low rainfall (A), and high rainfall (B). Note that the chlorinity in the open Gulf is close to 20%.

The bays have been subdivided into eight different environments in which sedimentary processes differ sufficiently to allow the sediments to be distinguished one from the other. Although borderline cases show gradations between two different types of sediments, in general the boundaries are sharp rather than transitional. Near boundaries, however, there is some interfingering of the types on either side. The geographical distribution of the environments and their sedimentary units in the Rockport area is shown in figure 3.

Bays Near Mainland

The narrow shallow zone which follows most of the shore of the mainland (so far as it has been studied) contains sediments which are preponderantly terrigenous quartz sand (fig. 4A). These sediments, however, differ distinctly from the clean sand sediments in the narrow beaches, which occur along portions of the bay shores, in that these bay sediments contain appreciable quantities of silt and clay and the content of shells and Foraminifera is higher than in the bay beach samples in their vicinity. The zone appears to have rather definite limits but has not yet been thoroughly studied.

Bays Near Rivers

In a rather extensive zone in the upper part of San Antonio Bay, the sediments have been greatly influenced by the entering fresh water and its suspended sediment. Plant fibres and ostracods are important items, especially in the samples collected in Mission Lake[7] where most of the river water now enters. These Mission Lake samples have far more ostracods than Foraminifera, contrary to the sediments in all other environments of the Rockport area. The sediments contain a high percentage of clay (note triangle in fig. 4A) and the coarse fraction is predominantly terrigenous. The percentage of coarse fraction in the "pie" diagram is slightly higher than the average of the triangle diagram. It should be noted, however, that the latter is based on far more samples than the "pie" diagram for the same environment and is therefore more representative.

Some of the cores near the river mouths have laminated clays and silts (fig. 5A), which is in marked contrast to the other environments. Lamination also occurs in the sediments bordering the Mississippi Delta (see accompanying paper by P. C. Scruton).

The Guadalupe and its tributary San Antonio River apparently carry large quantities of finely comminuted calcium carbonate to the sea. This has caused a high content of carbonate in the sediments near the mouth of the Guadalupe River (fig. 6). This carbonate can not be a precipitation occurring chemically at the river mouth, because the carbonate is equally abundant in the samples taken from the river channel at various distances above the mouth.

Oyster Reefs

Surface sampling of the oyster reefs has proven impractical because of the shallow depths and the difficulty of obtaining representative samples. In coring operations (to be reported elsewhere) a considerable number of samples were obtained which consisted predominantly of oyster shells. Since these samples are very similar in character and come from areas near surface reefs, it may be presumed that they represent typical buried oyster reefs. The diagram (fig. 4A) shows an average of 13 samples from these borings. It will be seen that they are decidedly different from the sediments in all other environments.

Bays Near Oyster Reefs

In a series of samples taken across the long direction of Copano Bay, the influence of nearby oyster reefs is indicated.

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[7] Actually a part of San Antonio Bay as it is connected by a narrow strait.

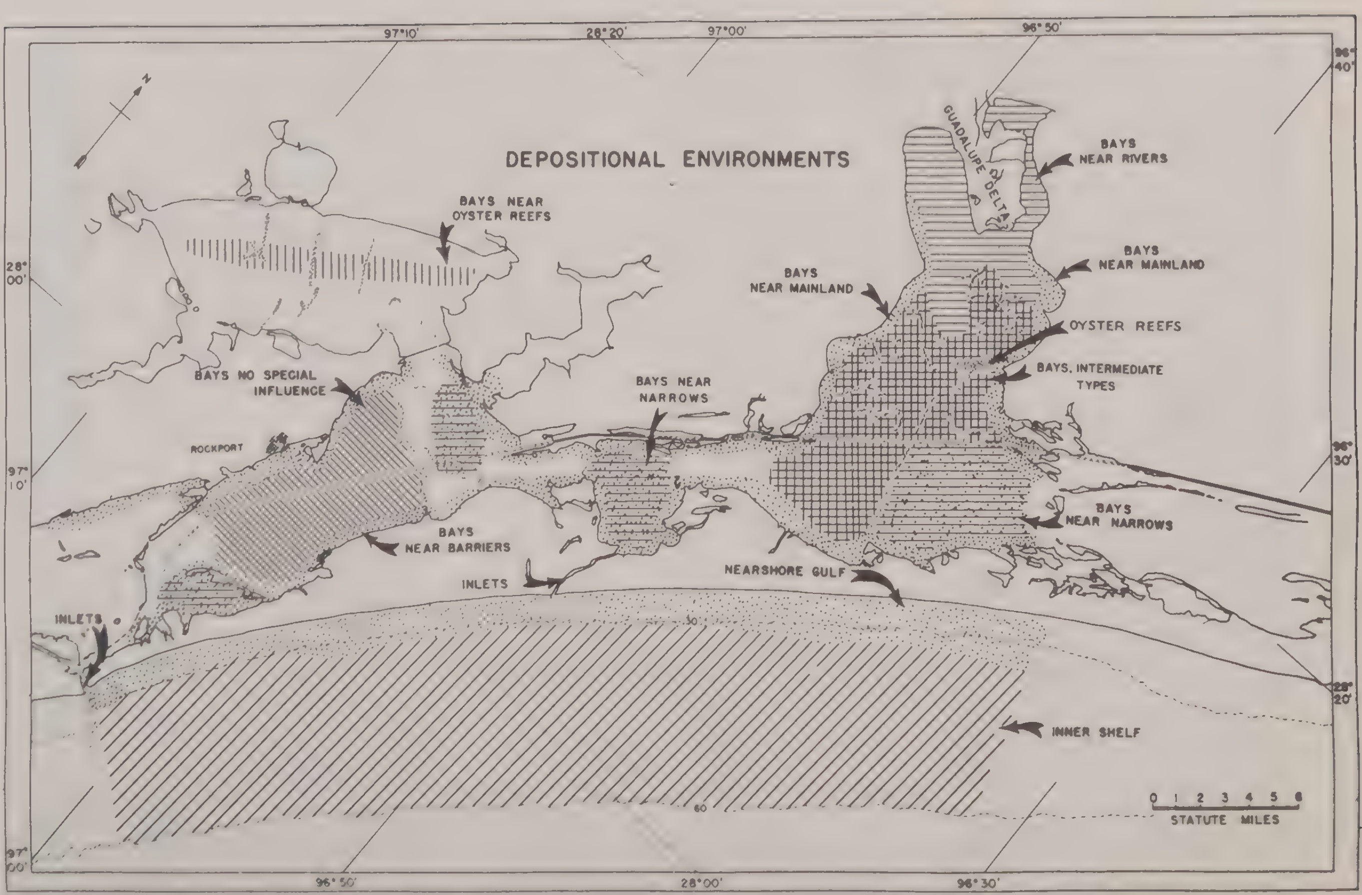
DEPOSITIONAL ENVIRONMENTS
N
BAYS NEAR OYSTER REEFS
GUADALUPE DELTA
BAYS NEAR RIVERS
BAYS NEAR MAINLAND
BAYS NEAR MAINLAND
OYSTER REEFS
BAYS, INTERMEDIATE TYPES
BAYS NO SPECIAL INFLUENCE
ROCKPORT
BAYS NEAR NARROWS
BAYS NEAR NARROWS
BAYS NEAR BARRIERS
INLETS
NEARSHORE GULF
INLETS
INNER SHELF
30
60
0 1 2 3 4 5 6
STATUTE MILES
97°10'
28°20'
97°00'
96°50'
96°40'
28°00'
96°30'
97°10'
28°20'
97°00'
96°50'
28°00'
96°30'

FIG. 3. Environments of deposition in the Rockport area. Some of the boundaries are generalized. The "bays-near-oyster-reefs" are incomplete. Many examples occur near the reefs which are shown by the close-spaced dots.

The coarse fraction analyses show that shells constitute the bulk of the coarse fraction and also are an important element in the total sample. As in the oyster reef environment the bulk of the coarse fraction is coarser than 1.0 mm. This is due to the presence of a considerable number of broken oyster shells coming from the nearby reefs. Foraminifera are somewhat more abundant than in the sediments of "bays-near-rivers" environment and the proportions of silt and clay are quite variable as is shown by the triangle diagram. It is probable that the "bays-near-oyster-reef" environment is more restricted than the Copano Bay traverse (fig. 3) would indicate because Copano Bay has been the scene of an extensive shell industry. In any bay, however, where oyster reefs are present the flanks of the reef will yield sediment of high shell content and thereby fall into the "bays-near-oyster-reef" type. Some of the oyster reefs of San Antonio Bay are now buried by other types of sediment (Norris, 1953).

Bays, Intermediate Type

In the middle and in the southwestern part of San Antonio Bay the sediment can be considered as an intermediate type which shows some distant influence of the Guadalupe River along with some contributions from the small local oyster reefs and the nearby barrier island. The plant fibres of the "bays-near-rivers" environment are virtually missing and the terrigenous sediments are less abundant. The total percent of the coarse fraction varies along the length of this area, showing an increase to the south, so that it is distinctly higher in southwest San Antonio Bay than in the middle bay. This increase is presumably due to the greater proximity to the barrier island.

Bays, No Special Influence

Over extensive portions of the deeper part of Aransas Bay, the sediment is dominantly clay with a small but very distinctive coarse fraction. The ½-¼ mm and ¼-⅛ mm size groups consist almost entirely of Foraminifera, and terrigenous sediments are virtually missing except in the ⅛-1/16 mm sieving. The environment is influenced by having the greatest bay depths in this general area and by being situated farthest from the entering rivers. The effects of narrows and inlets and of oyster reefs are also slight in this zone. The triangle diagram shows that this environment has the highest clay content and the lowest sand content of all the types represented in the area.

It is notable that at a depth of between 60 and 120 cm in a long core from the "intermediate type" environment of central San Antonio Bay there is a change to the "bays-no-special-influence" type of sediment, suggesting that conditions similar to those of Aransas Bay may have existed also in San Antonio Bay in the past; possibly because of the greater depth producing a slower rate of sedimentation in San Antonio Bay at the time when the underlying material was deposited.[8]

Bays Near Narrows

Mesquite Bay, southeast San Antonio Bay, a portion of northeastern Aransas Bay and the bay inside Mud Island (southeast Aransas Bay) all have a type of sediment which is far higher in sand than are the other bay sediments except for those located near shores. The "bays-near-narrows" environment is so named because it seems to occur in areas where a current through a narrows, either from adjacent bays or from the open Gulf, is carrying a considerable quantity of sand into the area. It will be noted that the terrigenous sand content of these sediments constitutes more than 50 percent

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[8] Rates of deposition as indicated by the relative abundance of Foraminifera is discussed by D. G. Moore, Am. Assoc. Petroleum Geologists, August 1955 (in press).

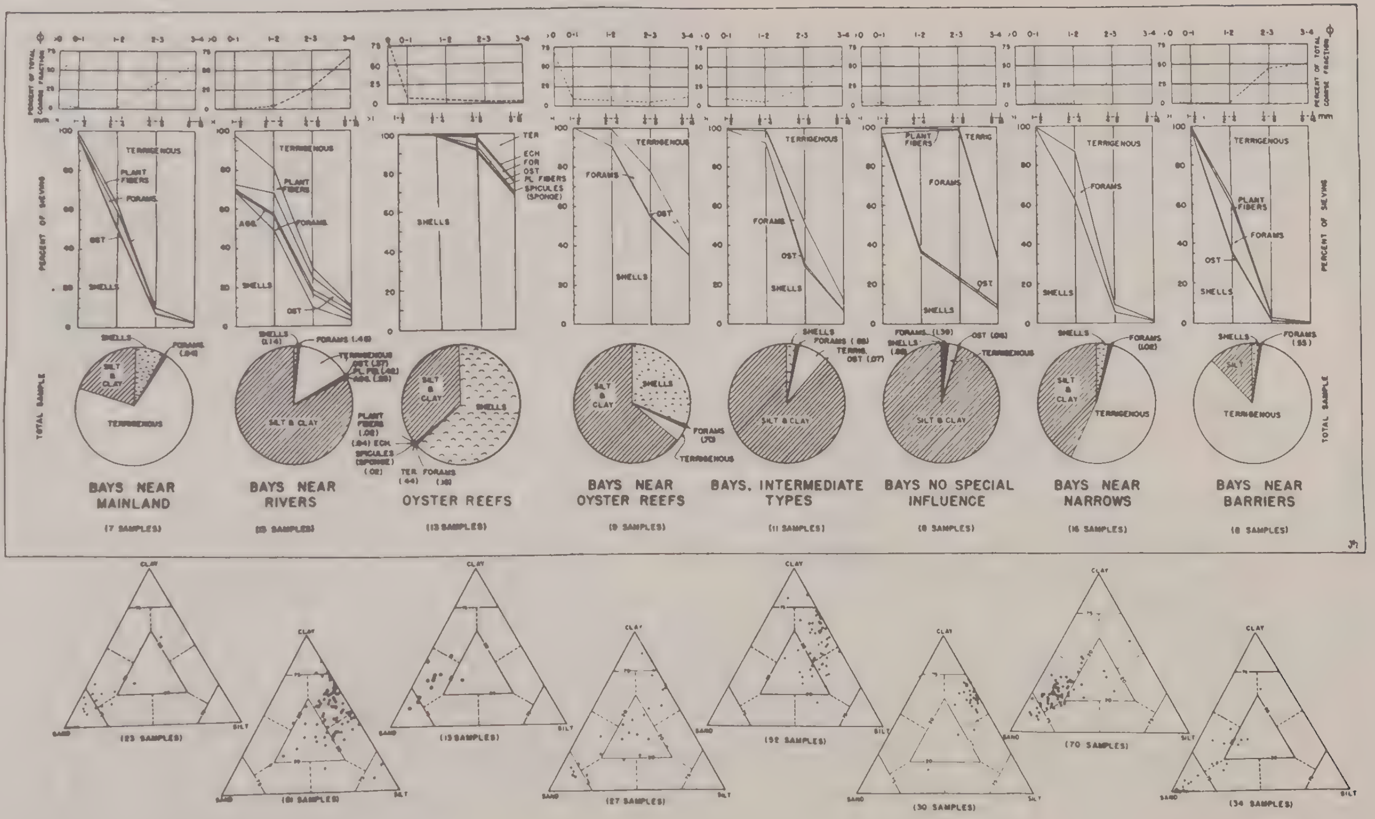


FIG. 4A.—Characteristics of bay environments as indicated by binocular microscope studies of coarse fraction sievings (three upper graphs), and triangle diagrams showing sand, silt, and clay of the samples from the same environments (lower diagrams). Note the total number of samples in the triangle diagram is considerably larger than for the binocular examinations which is because more size analyses have been made than coarse fraction estimates. Note: "Shells" refers principally to mollusc shells.

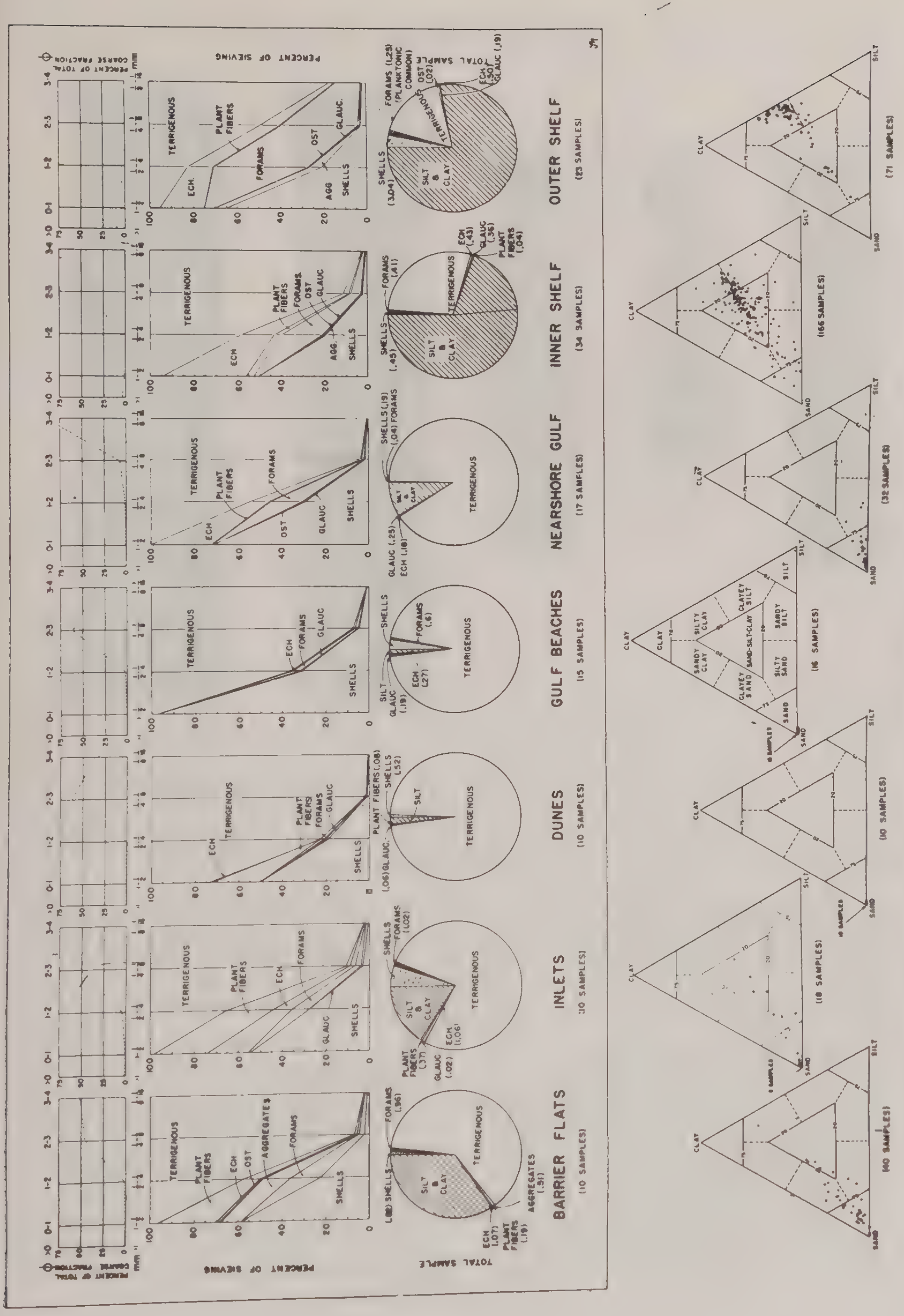


FIG. 4B.—Same information as in figure 4A for the barrier island and continental shelf environments.

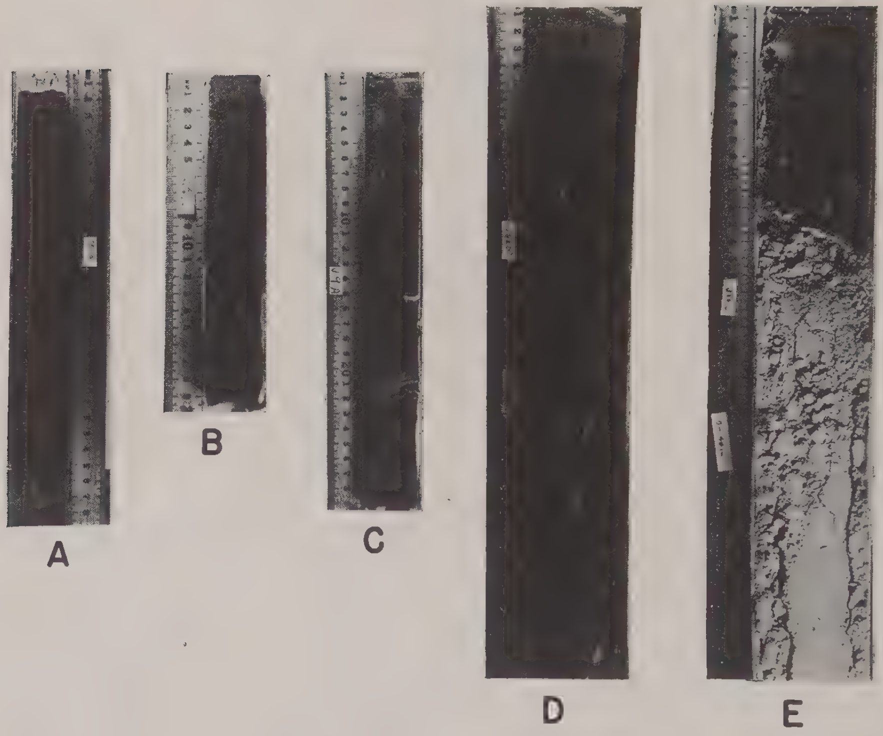


FIG. 5. Photographs of cores from the Texas area. A—laminae near the Guadalupe River. B—sand and silty clay lumps from lower San Antonio Bay. C—irregular sand lumps and lenses from the continental shelf. D—clay core lacking stratification on the outer shelf southwest of Aransas Pass. E—sand zone lying at a small depth below the surface on the outer shelf somewhat north of the Rockport area. Note the scales are in centimeters.

of the total sediment. Shells and Foraminifera are also relatively high. The triangle diagram shows, however, that despite the high sand content, clay is quite consistently more abundant than silt.

This dominance of sand and clay suggests periods of silty clay deposition alternating with periods during which large amounts of sand are either carried into the area by strong currents or concentrated from the other sediments by the winnowing of the finer material. Lamination might be expected to develop under these conditions, but actually it is extremely rare. Instead the cores show irregularly-shaped lumps of sand within silty clay or silty clay within sand (fig. 5B). Organisms which actively stir the bottom have evidently eliminated any lamination which may have existed.

Bays Near Barriers

Sediments in the vicinity of the barrier islands have terrigenous sands as the chief constituent whereas clay is largely eliminated and shells and Foraminifera are minor constituents. The environment is similar to the "bays-near-mainland" type, but differs as follows: (1) there are fewer Foraminifera and fewer shells, (2) there is virtually no clay in

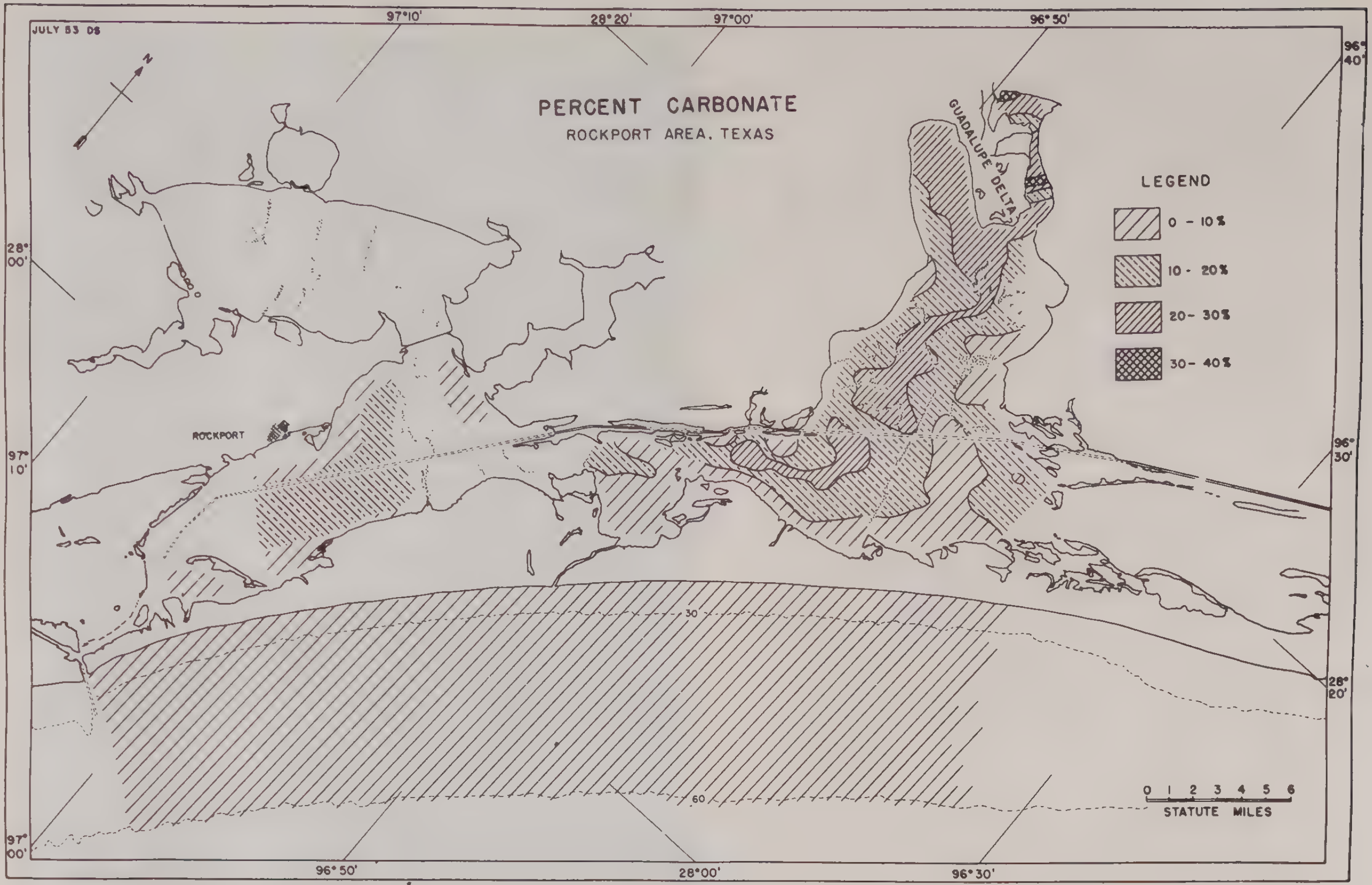

JULY 53 DS
N
PERCENT CARBONATE
ROCKPORT AREA, TEXAS
GUADALUPE DELTA
ROCKPORT
LEGEND
0 - 10%
10 - 20%
20 - 30%
30 - 40%
0 1 2 3 4 5 6
STATUTE MILES
30
60
97°10'
28°20'
97°00'
96°50'
96°40'
28°00'
97°10'
96°30'
28°20'
97°00'
96°50'
28°00'
96°30'

Fig. 6.—Percent carbonate content in samples from the Rockport area. Note the high percentages near the Guadalupe Delta. These figures are based on the gasometric method and the samples have had most of their shells removed before analysis.

the fine fraction, and (3) at comparable depths of water there is a greater amount of terrigenous sand. The last characteristic is probably the result of overwash and some wind transport across the islands.

General Sediment Units in the Bays

The preceding description of the environment indicates that there are three principal sediment units within the bays: (1) the silty clays which characterize the "bays-near-rivers," the "bays-intermediate-type" and "bays-no-special-influence," in all of these the fine sediment is introduced largely from the entering streams; (2) the clayey sands which are a mixture of the silty clays from the entering streams and the sands from inlets, barrier islands, and bay shores; (3) oyster reef or reef detritus.

BARRIER ISLAND SEDIMENTS

Description and Processes

The barrier islands have at least four distinctive environments (fig. 7). On the side toward the bays they usually consist of very low flat marshy areas with many ponds and channels. In the interior, there are rather extensive sand dunes and in some places, beach or dune ridges. The seaward portions consist of broad beaches extending the entire length of the islands.

Sedimentary processes on the barrier islands are more apparent than in most other localities. Waves along the flanks of the island form the beaches and have developed the even coastline. During hurricanes waves may form large overwash areas, occupying previously closed inlets and spreading over the marsh land

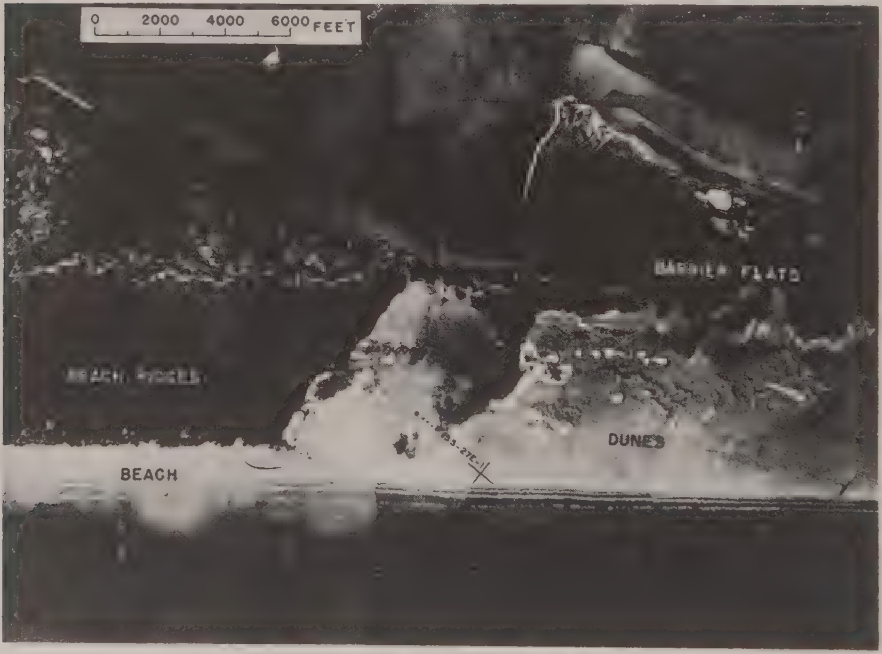


Fig. 7.—Aerial photograph of Matagorda Island illustrating the barrier island environments (courtesy of Edgar Tobin Aerial Surveys).

on the inside of the island. The prevailing southeasterly winds have formed dunes on the landward side of the beaches and, to a limited extent, have carried sand to the marsh areas and barrier flats on the leeward side of the islands. Current action is important principally in the inlets which traverse the barrier islands but are also of some effect in the small tidal ponds on the island itself. The strongest currents in the passes are the result of raised water levels resulting from wind stresses. These have been measured along the channel margin at velocities of up to two knots. Celestial tidal currents are of a much smaller magnitude but along the channel margin have been measured and found to average about 0.5 knot.

Barrier Flats

The marshy flat portions of the barrier islands with their ponds and inlets have a fairly characteristic sediment (fig. 4B). Terrigenous sand is even more abundant than in the "bays-near-narrows," although somewhat less abundant than in the zones that border the shorelines of the bay. Plant fibres form a distinct element in the material and echinoids are found in appreciable numbers. A small amount of caliche-like evaporite, largely of a calcium carbonate type, is found cementing some of the grains together into aggregates and forming powdery coatings around other grains. Locally these aggregates may become a dominant constituent. The triangle diagrams show that sand predominates but that clay is somewhat more abundant than silt.

Inlets

In the narrow passageways which cross the islands, sediments are found which have rather distinct characteristics. The terrigenous content is higher than on the barrier flats as are shells and Foraminifera. Plant fibres are also found, but the most distinctive feature is the echinoids which are extremely abundant in the coarser fractions. In some samples, the 1½ mm sieving consists almost entirely of echinoids. So far as has been found, this is not the case in any of the other environments. Glauconite, which is almost completely absent in the bays, is well represented in the inlet samples.

Dunes

The dune samples are characterized by their preponderant content of terrigenous sand and the very small amount of the fines which are largely silt. A small amount of comminuted shells exists and fibres constitute an important fraction particularly in the ¼ to ½ mm size. The absence of material of greater diameter than ½ mm is conspicuous in the Rockport area dunes. Some of the dune samples have a brownish color due to the presence of humus.

Gulf Beaches

Beaches on the seaward side of the barrier islands also have well-sorted fine sands, consisting predominantly of terrigenous material like the dunes, but having a larger content of shells and Foraminifera. The silt content is as low as in the dune sand. Echinoids are represented to some extent and there is a small amount of glauconite whereas plant fibres are virtually missing. In almost all cases where a dune sample was taken near a Gulf beach sample, the plant fibres and the lower shell and Foraminifera content of the dune sample formed the conspicuous differences. A study of the roundness of sand grains by Allan Beal of Scripps Institution shows that the dune sands are always more rounded than adjacent beaches.

Sediment Units of the Barrier Islands

The preceding description shows that barrier islands have two principal sediment units: (1) the sands of the beaches and the dunes, and (2) the silty or clayey sands of the barrier flats and the inlets. Sands are found also in some inlets and locally on the barrier flats.

CONTINENTAL SHELF SEDIMENTS

Description and Processes

The continental shelf along the Texas coast has an average width of about 60 miles. The slope is in general quite even but somewhat steeper near the coast. The shelf edge lies at about 50 fathoms (300 feet). Seaward of the barrier islands, there are at least three distinct environments represented in the Rockport area. Two others exist elsewhere along the Texas coast but are not found in the vicinity of Rockport.

In the open Gulf the relatively short period waves which characterize the Gulf of Mexico are effective only in shallow water and result in the rather sharp boundary between sand and finer sediments at a depth of about 35 feet. Nearshore processes in the open Gulf are more intensive than those of the bays because of the larger size of wind waves and the additional factor of swell from distant storms. Wave-generated longshore currents are effective along the length of the islands whereas rip currents such as are visible in figure 7 carry sand seaward to mix with finer sediments. The effects of tidal, wind-induced, and large scale semipermanent currents are less well understood and have not been measured in this area. Presumably currents even affect parts of the outer shelf as is shown by the uneven distribution of sediment sizes where depths are too great to expect effective wave action.

Nearshore Gulf

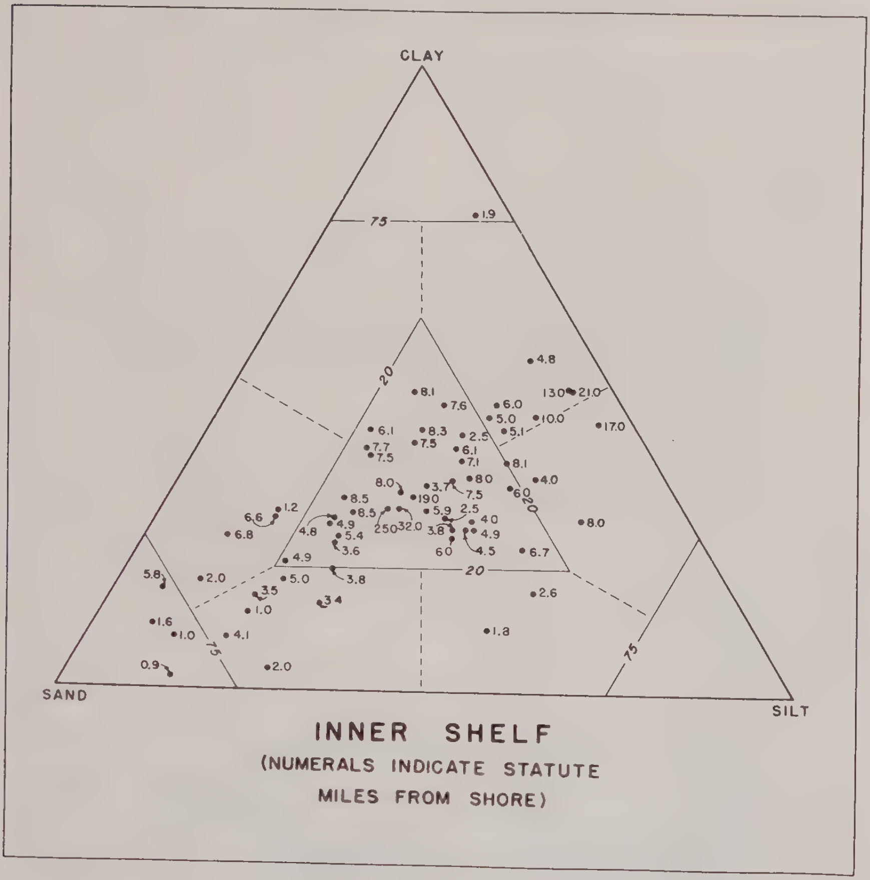
Extending out to about 35 feet of water, there is a sandy zone which parallels the coast line. The amount of silt mixed with the sand approximates that found in the "bays-near-barriers" environment but there is a conspicuously smaller amount of shells and Foraminifera on the Gulf side of the barrier, apparently due to the violent action of waves which has destroyed the organisms to a great extent. Like most other portions of the open shelf, the nearshore zone contains an appreciable amount of echinoids and glauconite.

Inner Shelf

Extending from depths of 35 feet to somewhat over 100 feet, is a sediment zone of rather indefinite boundaries in which sand, silt, and clay occur in about equal proportions. The relatively high silt to clay ratio in the fine fraction forms a contrast with typical bay sediments where clay is ordinarily dominant over silt. The terrigenous material in the coarse fraction continues to be the most important item. Shells and Foraminifera are more abundant in this zone than nearshore and also glauconite and echinoids show some increase and are always present. The sand occurs in pockets and lenses on the inner shelf (fig. 5C). Only a very slight correlation exists between sand content and distance from shore (figs. 8 and 9).

Outer Shelf

A somewhat arbitrary line at 120 feet (20 fathoms) has been used to divide the inner and outer shelf. There is no sharp demarkation but a gradual change in characteristics. On the outer shelf, southeast of Aransas Pass, silt and clay constitute about 99 percent of the sediment and terrigenous material is relatively low in the coarse fraction (fig. 9). Farther north, however, where the largest number of samples have been taken by the project, the outer shelf has a much higher content of sand (see triangular diagram, figure 4 and figs. 5E and 9). In the average outer shelf sample, shells and Foraminifera are far more abundant than in the inner shelf material. In several of the samples, southeast of Aransas Pass, Foraminifera are found to constitute 80 to 90 percent of the ½-¼ mm and the ¼-⅛ mm sievings. Most of these Foraminifera are planktonic in contrast to the very rare occur-



INNER SHELF

(NUMERALS INDICATE STATUTE
MILES FROM SHORE)

FIG. 8.—Relation of sand, silt, and clay to distance from shore of samples taken on the inner shelf.

rence of planktonic Foraminifera in the other zones. Echinoids and glauconite continue to be represented in most samples.

The greater quantity of sand found to the north of Aransas Pass may represent sediment derived from a residual sand mass related to Pleistocene lowered sea levels.

Sediment Units on the Continental Shelf

The preceding discussion shows that the shelf has at least three sediment units: (1) the sands which occur in the shallow water along the shore and locally well out on the shelf, (2) the sand-silt-clay sediments of the inner shelf at a moderate distance from shore, and (3) the silty clays of the outer shelf.

TYPICAL TRAVERSES FROM BAYHEAD TO OUTER SHELF

The preceding discussion has shown the changes in the nature of sediment extending from the inner portions of the bays across the outer bays over the bar-

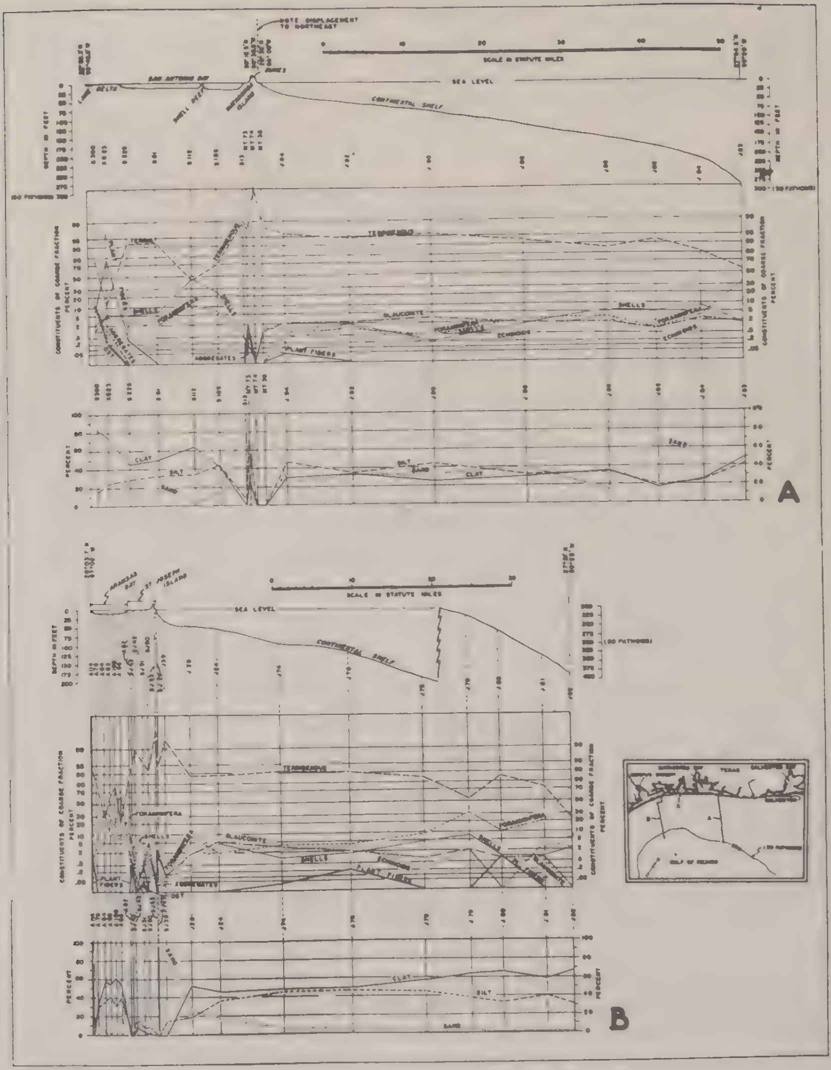


FIG. 9A and B—Variation in constituents and grain-size of sediment in lines extending from the coast across the bays, barrier islands, and the continental shelf. The constituents are plotted on an arithmetic probability graph because of the necessity of an expanded scale at high and low percents. Note that section A is broken at the outer edge of Matagorda Island in order to show the different type of shelf sediment somewhat north of the Rockport area. The plant fibers on the open shelf in J 94 (line A) are a reflection of the Colorado River which enters in the near vicinity.

rier island and out across the continental shelf. In order to give a graphic picture of the changes which take place in sediments deposited in what is believed to be a typical series of Texas coast environments, figure 9 has been constructed, giving depth profiles and the variation in the principal constituents of the coarse fraction along the traverses. A graph is included which shows the variations in the content of sand, silt, and clay along the same traverses.

It will be noted from these traverses that there is by no means a decreasing grade size between the inner coast and the outer edge of the shelf. The sections show a general pattern of fine materials in the bays, becoming coarser near the barrier island, reaching the coarsest grade size in the beaches and dunes but decreasing outward rapidly near shore and discontinuously farther out across the shelf. This finding is in keeping with the traverses of the Texas shelf reported by Stetson (1953).

This pattern of alternate decrease and increase in grain-size going seaward from the mainland shoreline can be understood if it is borne in mind that not all of the sediment from the land moves directly seaward, but a great deal of it moves along the coast. The barrier island sands are a product of such transportation. Following the development of the barriers the newly created lagoons form settling areas for fine sediment which produces the enigma of fine material being deposited inside coarse material. Similarly on the open shelf, residual sand bodies, presumably of Pleistocene age, cause great variation in the grain-size of the adjacent sediments. Where this sand is transported along the contours of the shelf, it results in coarser sediment than that found in those adjacent shoreward areas which lack a sand source.[9]

SEDIMENTS IN SIMILAR AREA

Sampling operations in API Project 51 have been concentrated in the Rockport area[10] but a few additional samples have been obtained from bays extending from near the Mexican border north to Galveston. Examination of these samples has indicated that sediment characteristics are relatively constant within similar environments along the Texas coast. Not all of the environmental types of the Rockport area have been obtained in the other areas, but this is probably related more to the scarcity of samples than to the absence of any of the environments.

Some of the characteristics which apply to areas north of Rockport as well as to the Rockport area, are: (1) wood fibres occur in the samples of the "bays-near-rivers" environment, (2) glauconite is common on the open shelf and almost completely absent in the bays, (3) echinoids are abundant on the open shelf and in the inlets whereas they are rare in the bays, (4) Gulf beaches and dunes have clean well-sorted sand, (5) shells and Foraminifera are scarce in the beaches and rare in the dunes, (6) planktonic Foraminifera are abundant on the outer shelf, scarce on the inner shelf, and almost completely absent in the bays.

In Laguna Madre, to the south of the Rockport area, high evaporation in the bay appears to have influenced the sediment by coating the sands with powdery calcium carbonate which is a caliche-like form of evaporate. Locally the sands are cemented by this precipitate.

On the open continental shelf to the east of Galveston, there are a series of banks where the sediments (given us by Magnolia Petroleum Company) differ strikingly from the typical sediments of the Rockport area. Great masses of broken shells, all of them apparently dead, are found on these banks. According to R. H. Parker[11] the shells represent conditions somewhat warmer and perhaps deeper than those now existing. In the vicinity of these banks, the percentage of sand-size material is far greater than at comparable depths off the Rockport area.

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[9] For additional discussion of variation of grade size away from the coast see Emery (1952) and Shepard (1948).

[10] Another area of concentration is discussed in the accompanying paper by P. C. Scruton.

[11] Biologist with A.P.I. Project 51.

An unusual environment is found where the Brazos River empties directly into the ocean. Here the one available sediment sample has a considerable amount of wood fibres but is predominantly silt and clay, with almost a complete absence of the shells and Foraminifera which characterize most shelf sediments. This sample represents an environment where large amounts of fine sediment are being poured into the ocean from entering rivers. It is more comparable to the sediments off the Mississippi Delta[12] than to anything in the area to the south.

It is impossible to say at present whether the many bay environments of the Texas coast are found in other areas. It may not be over-speculative to suggest, however, that very similar types of sediments will be found along most coasts where there are barrier islands separating a coastal plain from the continental shelf.

APPLICATION OF METHODS

If an attempt is made to find the environment of an ancient sediment by comparing its characteristics with the graphs indicated in figure 4, it should be remembered that very few samples will agree in all respects closely to the diagrams. The important point is to study a sample to see which environment it most closely resembles. This can be done partly by a process of elimination. It is well also to bear in mind the important features of each environment which may be more significant than the actual percentages shown in the graphs. Furthermore, some of the constituents in older environments may have been removed or depleted by diagenesis. Each situation should be given special attention to get the best results.

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[12] See accompanying paper by P. C. Scruton.

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SEDIMENTS OF THE EASTERN MISSISSIPPI DELTA[1]

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ABSTRACT

The Mississippi Delta is building because the rate at which sediments are supplied is faster than the combined effect of the rate at which they are removed by waves and currents and the rate the delta area is subsiding. River load is discharged into a variety of depositional environments in the Gulf of Mexico. These environments are inter-related, gradational, and persist both laterally and through some depth of water. Sedimentary deposits being formed in these environments have different lithologic and petrographic characteristics but also are related and gradational. Differences between environmental factors and processes produce the lithologic and petrographic differences and also produce correlative differences in depositional rates. Continuing delta growth causes seaward migration of these environments and leads to the formation of deposits, or sediment units, of large areal extent which bear some predictable relationships to each other.

Sedimentary units which are almost entirely the products of river-borne material in order of seaward occurrence are: (1) "marsh deposits," (2) "delta front silts and sands," (3) "prodelta silty clays," and (4) "offshore clays." These units are deposited approximately concentric to distributary mouths and are analogous to the topset, forset, and bottomset beds of classic delta description. Their characteristics depend to a large extent on the distance from source and depth of water. Another unit, "marginal deposits," generally occurs between the deltaic clays and outlying sands from marine sources. Marginal deposits have characteristics transitional between the clays and the outlying sands.

INTRODUCTION

The Scripps Institution of Oceanography, with a grant from the American Petroleum Institute, has been studying the recent sediments in the Gulf of Mexico and their environments of deposition. The purposes of these studies are to learn more about the basic principles of sedimentation and to develop criteria for recognition of environments of deposition in older rocks.

The eastern side of the Mississippi River Delta was chosen as one of the regions to be examined, because sediments are being deposited there very rapidly by the distributaries or branches of the river. All of the beds formed by delta building over the pre-existing continental shelf have been investigated, but marine beds have received the emphasis because the completed delta is deposited predominantly below the surface of the Gulf of Mexico.

Five separate trips were made to collect data at different seasons of the year and at different high and low stages of river discharge. A total of more than five months was spent in the delta. Over six hundred and fifty sample locations were occupied, and cores were collected at most of them. The gross lithology of the cores has been studied in the field and at the Scripps laboratory. Studies were made of the coarse fraction (sediment retained on 0.062 mm sieve) as described by Shepard and Moore (1954) and by grain size analyses. In addition a large number of measurements have been made, at different seasons of the year, on the currents and the temperature, salinity, turbidity, and chemistry of the water. These measurements aid in understanding the environments of deposition.

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[1] Contribution from the Scripps Institution of Oceanography, New Series No. 792. This investigation was supported by a grant from the American Petroleum Institute, Project 51.

[2] Stanolind Oil and Gas Company, Tulsa, Oklahoma. Acknowledgments: Appreciation is extended to F. P. Shepard, Director of Project 51, and to R. S. Arthur, M. N. Bramlette, D. G. Moore, F. B. Phleger, and D. M. Poole for their numberless helpful suggestions and comments made both during the course of investigation and the preparation of the manuscript. Special thanks also are due John G. Bartram and Parke A. Dickey for their encouragment and help with the manuscript and to the Stanolind Oil and Gas Company which generously made time available to complete the work.

The Mississippi Delta has been studied by many other geologists and engineers. Exhaustive reviews of the literature on the delta have been published by R. J. Russell (1936) and Russell and Dohm (1936). Trowbridge (1930), Russell and Russell (1939), and Morgan (1951) have included extensive bibliographies in their publications. The most recent publications have been by Fisk (1944, 1952, 1954), Morgan (1951, 1953), and Bates (1953).

The purpose of this report is to describe briefly the physical processes and factors operating in the depositional environments and the different kinds of sediments of the Mississippi Delta, and to show how these processes and factors produce the different sediments. The sediments vary in a regular manner seaward from shore but are relatively uniform parallel to the shore. The seaward variations of lithology, grain size, and coarse fraction are the basis for subdivision of the deltaic sedimentary wedge into lithologic units. Another report is planned to present more detailed descriptions of the sediments and the environments of deposition.

HISTORY OF MISSISSIPPI DELTA

During Teritary and Quaternary times many rivers in the southern part of the United States flowed south into the Gulf of Mexico. They transported vast amounts of sediments and discharged them into the ocean at the river mouths. These sediments which were either deposited immediately or were transported laterally by waves and currents and later deposited now constitute the great mass of Tertiary and Quaternary shales and sandstones in the Gulf Coast region. Slow and probably almost continuous crustal subsidence during this time has carried much of this material to great depths where it has been buried by younger deposits. At different times during this period, the sea has regressed southward and transgressed northward. The net result has been a southward regression of the shore, however, because sediments were deposited more rapidly than subsidence occurred. The modern Mississippi Delta represents one of the types of deposits formed during this long history of deposition and subsidence.

Waxing and subsequent waning of Pleistocene glaciation affected the Mississippi River and the modern delta in two different ways. First, the advance of the ice sheet into northern United States blocked the channels of several northward-flowing rivers, such as the Missouri River in Montana and the Monongahela River in Pennsylvania, and forced them to cut new channels into Mississippi River drainage. This created one of the world's great river systems and gave the Mississippi River a vastly expanded drainage basin from which to draw clastic sediment for transport to the Gulf of Mexico.

Second, during maximum expansion of the continental ice sheets in the Pleistocene, the shoreline must have regressed seaward to one of its most southern points. When the ice melted, sea level was raised and the shoreline transgressed northward. The sea advanced rapidly over a surface previously exposed to subaerial conditions into a valley which had been eroded by the enlarged river to the lowered baselevel of the Pleistocene sea. Thus, in the present Lower Mississippi Valley, the sea probably entered a relatively wide trough and formed an embayment or estuary (pl. I). Earlier deposits of the Mississippi and other rivers of the area were submerged and subjected to further erosion, winnowing, and transportation by waves and currents. Off the coast of Mississippi and east of the modern delta there now exist extensive sheets of sand sorted in this manner from sediments originally derived from rivers to the east. These sands contain a different mineral assemblage than the Mississippi River sands and are called Eastern Gulf sands.

During stabilization of sea level the Mississippi River with its great flow of fresh water and heavy load of sediment began building new land southward. This land was formed and the shore line was pushed rapidly southward because the river supplied sediment faster than it could be removed by waves and currents and faster than the area was subsiding.

As deposits of the Mississippi River have grown seaward in post-glacial time, the positions of the river mouths have not stayed in one place. Whenever the accumulation of sediments has overextended the river, the resulting gradient disadvantage has caused a shifting of the direction of discharge. Many such shifts in position of the river mouths occurred during building of the shoreline to its present position. The Teche and Lafourche are older subdeltas west of the present one. The St. Bernard Subdelta lies farther north and built

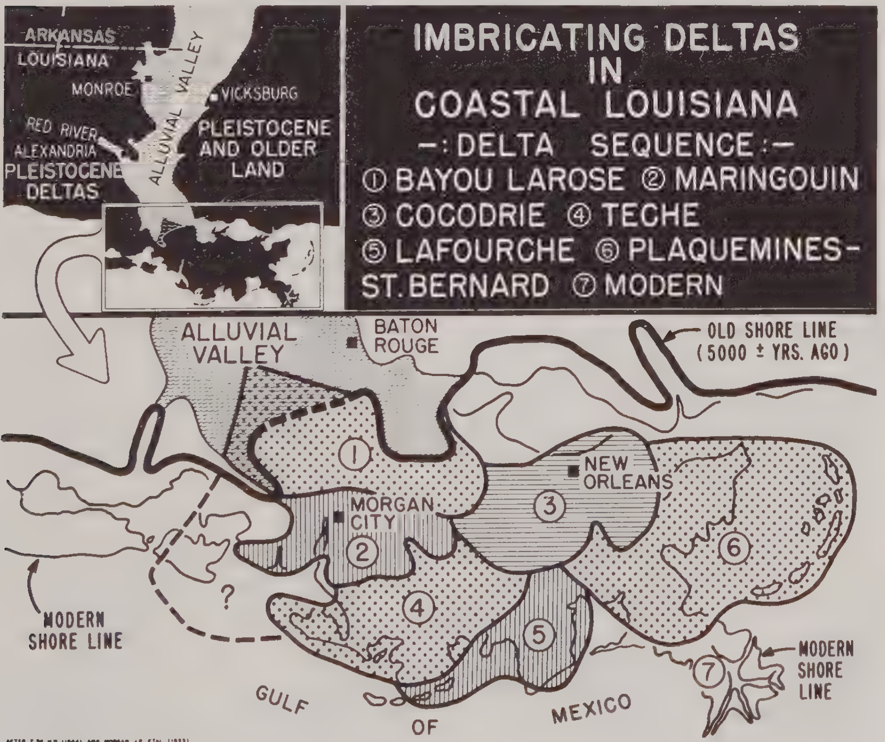
ARKANSAS
LOUISIANA
MONROE
VICKSBURG
ALLUVIAL VALLEY
RED RIVER
ALEXANDRIA
PLEISTOCENE DELTAS
PLEISTOCENE AND OLDER LAND
IMBRICATING DELTAS IN COASTAL LOUISIANA
—: DELTA SEQUENCE :—
① BAYOU LAROSE ② MARINGOUIN
③ COCODRIE ④ TECHE
⑤ LAFOURCHE ⑥ PLAQUEMINES-ST. BERNARD ⑦ MODERN
ALLUVIAL VALLEY
BATON ROUGE
OLD SHORE LINE (5000 ± YRS. AGO)
NEW ORLEANS
MORGAN CITY
①
②
③
④
⑤
⑥
⑦
?
MODERN SHORE LINE
GULF OF MEXICO
MODERN SHORE LINE

Plate I.—Step-by-step development of the Mississippi River's delta complex in coastal Louisiana.

eastward into the present Chandeleur Island area. The Plaquimines (Forts) subdelta was built mostly near the site of the present active delta (pl. I).

Rapid seaward advance of the shoreline of each of the subdeltas during their constructional phases is followed by a slow retreat when the river is diverted to a different area of discharge. This shoreline retreat may in part be the result of compaction of sediments and regional subsidence, but it is also the result of marine erosion, winnowing, and removal of previously deposited sediments. This is the destructional phase of a delta's history. Extensive sand areas on the sea floor south of the Teche and Lafourche subdeltas and east of the Chandeleur Islands are the result of sand concentration during this destructional phase.

These sand sheets mark the limit of seaward advance of one delta and may be overlapped and buried by the sediments of younger deltas. Because these deltas were built upward to sea level in water which gradually deepened to the south, they each consist of a wedge or embankment of sediment thickening seaward (pl. 2). The coastal area of Louisiana consists of an imbrication of several such wedges. Plate I shows the step-by-step development of the deltas in coastal Louisiana; plate II shows the morphology of the modern delta and its relationship to older deltas and the pre-existing continental shelf and slope.

A part of the sand area east of Breton and the Chandeleur islands and north of the present delta is shown in figure 1. It is most important to remember that this mass of sand is not being deposited by the present delta, but was produced by wave and current erosion and winnowing of sediments deposited as the earlier St. Bernard subdelta. Still farther northeast near Cat Island, this residual St. Bernard sand body merges into the larger mass of Eastern Gulf sands previously described.

Deposits of the modern Mississippi Delta are representative of some of those constituting the great mass of Gulf Coast Tertiary sediments. Building of the modern delta is one of a series of similar events which has filled the Post-Glacial Mississippi estuary and built out the coast of Louisiana. Therefore, the modern delta also should be representative of the individual wedges which make up this large deposit (pls. I and II).

SEDIMENTARY PROCESSES

At the point where a large river meets the sea many powerful and conflicting physical forces and processes control the distribution and deposition of sediments. The work described in this report was undertaken to get more and better data on these conditions and their effects on the sediments. It is hoped that by recognition of the processes producing the lithologic, structural, and organic characteristics of the sediments of the modern delta, it may be possible to better interpret ancient sediments deposited in similar deltas.

Forces producing water motion and physical processes that are recognized in the Mississippi Delta include the following:

1. Seaward flow of fresh water due to conserved momentum
2. Currents in and around distributary mouths, due to density differences, mixing between masses of fresh and salt water, and also due to hydraulic head
3. Tidal currents
4. Wind waves and longshore currents due to waves
5. Large scale wind-driven currents
6. Regional, semi-permanent currents
7. Differential settling of particles
8. Turbidity currents and slumping
9. Diffusion.

These forces and processes are acting simultaneously to supply and distribute varying amounts of different kinds of

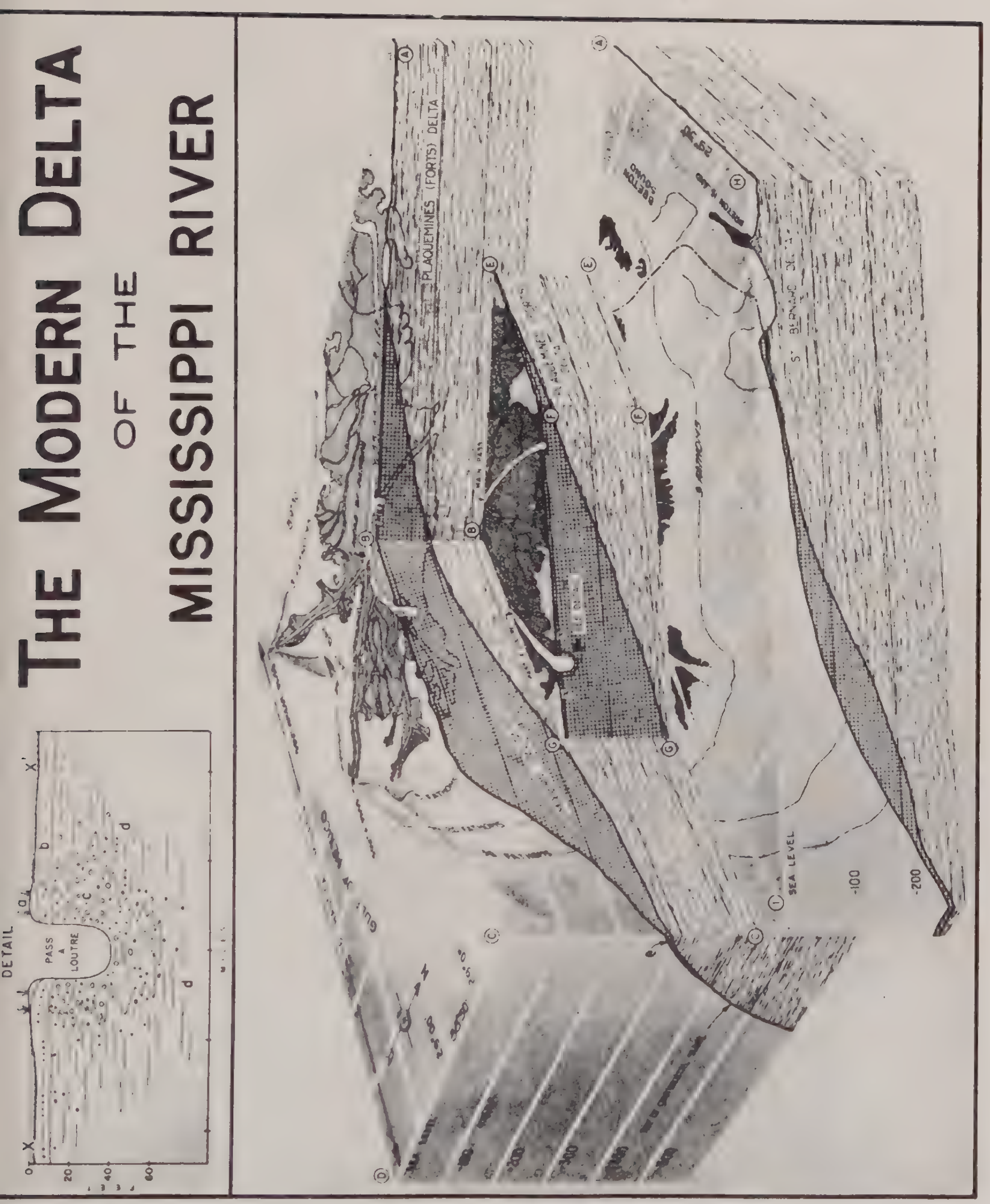
THE MODERN DELTA
OF THE
MISSISSIPPI RIVER
DETAIL
PASS A LOUTRE
X
X'
a
b
c
d
0
20
40
60
PLAQUEMINES (FORTS) DELTA
BRETON SOUND
ST BERNARD DELTA
MAIN PASS
SEA LEVEL
-100
-200
A
B
C
D
E
F
G
H
I

PLATE II.—Morphology of the Modern (Balize) Delta of the Mississippi River and its relationships to
der deltas and the continental shelf and slope. Distances seaward toward deposits of the older deltas ex-
nded are unknown. Detailed cross section X-X′ shows spatial relations between (a) marsh deposits (includ-
g natural levees), (b) shallow water delta front silts, (c) delta front sands and silts formed off large
stributaries, and (d) pro-delta silty clays. (e) indicates the horizon of offshore clays.

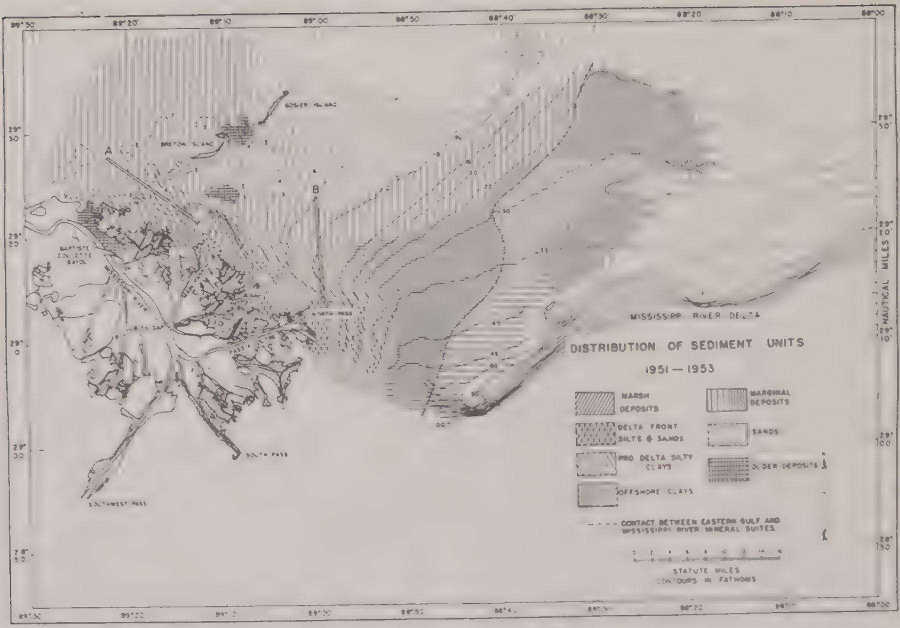
MISSISSIPPI RIVER DELTA
DISTRIBUTION OF SEDIMENT UNITS
1951 — 1953
MARSH DEPOSITS
MARGINAL DEPOSITS
DELTA FRONT SILTS & SANDS
SANDS
PRO DELTA SILTY CLAYS
OLDER DEPOSITS
OFFSHORE CLAYS
CONTACT BETWEEN EASTERN GULF AND MISSISSIPPI RIVER MINERAL SUITES
STATUTE MILES
CONTOURS IN FATHOMS
NAUTICAL MILES
BRETON ISLAND
CHANDELEUR ISLAND
BAPTISTE COLLETTE BAYOU
NORTH PASS
SOUTH PASS
SOUTHWEST PASS
A
B
89°30
89°20
89°10
89°00
88°50
88°40
88°30
88°20
88°10
88°00

FIG. 1.—Note! Varied cross-hatching in offshore clay and marginal deposits indicates different mineral suites.

sediments. They also react on each other so that their effects may cancel or be additive. In addition they exhibit fluctuations of intensity with periods that range from very short to annual or longer, some of which occur regularly and some at random. In all of the processes involving water movement, turbulence also is an important factor. Despite this great complexity it is possible to recognize dominant processes in some areas and to interpret their effects.

A great volume of fresh water, loaded with sediment ranging in size from sand to clay, flows into the Mississippi Delta where the main river channel breaks up into the numerous large and small distributaries. Each of these distributaries has a different rate of flow which, of course, varies greatly between different seasons of the year.

During about one-third of each year, the discharge of the Mississippi is great enough so that only fresh water flows in the distributary channels. Under these conditions the entire cross-sectional areas of the channels are occupied by seaward-moving fresh water and sediment. Bed load, suspended load, and all sediments deposited in the channels under previous, lower discharge conditions are transported out to the ends of the distributaries and delivered to the Gulf. The topographic form of the larger distributaries, including depth, width, and both the distributary mouth bars and flaring distributary mouths, are developed under these high discharge conditions. Distributary mouth bars and the flaring natural levees at the seaward ends of the distributaries are formed where the light fresh water meets and flows out over more dense Gulf water beneath. River water is buoyed up by the sea water. The layer of river water is thinned in this manner and therefore is forced to spread laterally to accomplish the same discharge. The distributary mouth bars and flaring natural levees are the streamlining topographic forms which develop in response to this dynamic situation.

During the remaining two-thirds of the year, discharge of the river is low enough so that the entire capacity of the distributary channels is not required to conduct river water seaward. Under these conditions dense salt water creeps over the bars and flows upstream in the distributary channels beneath seaward flowing river water. The salt water encroaches landward for distances up to about 125 miles. These distances constantly vary with the rate of river flow, the tides, and the winds. Intrusion of sea water into the distributaries forms what is called the "salt wedge." The top surface of the salt wedge is continually eroded along its length by mixing with river water, so that river water may already contain appreciable quantities of salt when it finally is discharged into the Gulf. Bed load of the river cannot be transported seaward of the upstream end of the salt wedge, because there is no downstream current present on the bottom. In the same way much material being transported seaward in suspension is deposited when it is trapped by settling into the underlying salt wedge. These soft oozy deposits, formed in the river channel during low water, are flushed out into the Gulf over the distributary mouth bars during succeeding flood stages, however.

Because of these processes which are the result of "system dynamics" there is an annual fluctuation in both size characteristics and amount of sediment delivered to the Gulf which is independent of any other factors. The greatest volume of coarsest material is transported to the Gulf during high water. Less material of finer size is transported during the remainder of the time.

At the mouths of the distributaries where the river meets the Gulf of Mexico, conditions also are complex. The general effects of the physical processes controlling sedimentation in the Gulf during flood stages are as follows. The moving mass of fresh water with its load of sediments flows into the Gulf out over sea water which has a greater density. Movement of the sea water is the result primarily of waves, tides, winds, and regional currents, but also is produced by the fresh water being discharged. In several different but interrelated marine environments, the sediments settle to the bottom to form the delta deposits. Under low river stages, this chain of sedimentary events is initiated in the river at the upstream end of the salt wedge rather than in the Gulf.

Because the light river water flows out on top of the salt water, its velocity is not completely checked immediately. Sediment deposition begins as soon as the river water passes the crest of the bar and leaves the confines of the distributary channel. In addition, bed load and material eroded from the channel bottom is moved up to the bar crest, shoved over into the Gulf, deposited, and helps to build the bar seaward. Suspended particles of different size, weight, and shape settle at different velocities. Rapidly settling sand is abundant in the samples collected close to the channel mouths, although sand is the least abundant material in suspension. Silt and clay are also settling to the bottom with the sand, however, so that even the first deposits seaward of the bar crests contain all three kinds of material and are not just clean sand. This can be seen schematically in figure 2, which was drawn to show the relationships between the change in suspended load, size composition of sediments, and rate of deposition.

Finer sediment is retained in suspension, in part because of turbulence, and is more widely distributed by the decelerating river flow and by wind, tidal, regional, and other currents. Diffusion associated with large, horizontal eddies

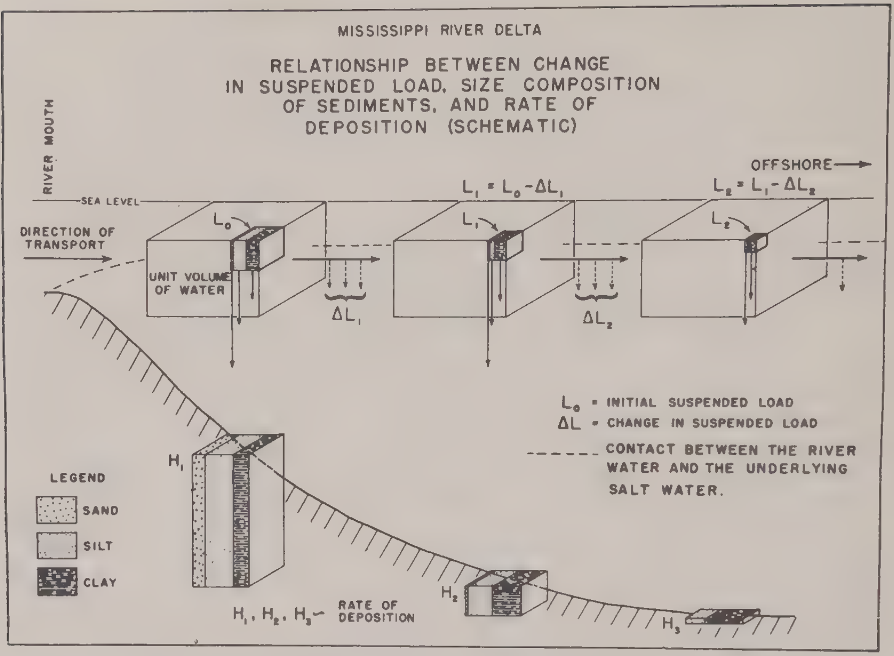
MISSISSIPPI RIVER DELTA
RELATIONSHIP BETWEEN CHANGE IN SUSPENDED LOAD, SIZE COMPOSITION OF SEDIMENTS, AND RATE OF DEPOSITION (SCHEMATIC)
RIVER MOUTH
SEA LEVEL
OFFSHORE
DIRECTION OF TRANSPORT
UNIT VOLUME OF WATER
$L_1 = L_0 - \Delta L_1$
$L_2 = L_1 - \Delta L_2$
L_0
L_1
L_2
ΔL_1
ΔL_2
L_0 = INITIAL SUSPENDED LOAD
ΔL = CHANGE IN SUSPENDED LOAD
------ CONTACT BETWEEN THE RIVER WATER AND THE UNDERLYING SALT WATER.
LEGEND
SAND
SILT
CLAY
H_1
H_2
H_3
H_1, H_2, H_3 – RATE OF DEPOSITION

FIG. 2.—Open blocks represent a unit volume of water with the amount and kind of suspended sediment shown schematically by the enclosed smaller blocks. Solid vertical arrows from the small blocks are proportional to the settling velocities of sand, silt, and clay. Initial sediment load (L_0) is continuously decreased in amount and kind by the change in load (ΔL). The amounts of sediment deposited and the proportions of sand, silt, and clay in bottom deposits are related to settling velocities and distance from river mouth. Outward changes in the size composition of bottom sediments are shown by blocks H_1, H_2, and H_3. The heights of these blocks are proportional to the rates of deposition which decrease seaward.

also may be important. Particle size characteristics of the transported load change with increasing distance from distributary mouths, and smaller particles become relatively more abundant both in suspension and in the deposits. The suspended load decreases constantly during transportation, and the direction of distribution changes with fluctuating currents. Therefore, a lesser amount of sediments is spread over a larger area, and the rate of deposition decreases with increasing distance from the source. Additional material of marine, not river, origin is added to the sediments by the growth of marine organisms and by lateral migration of sands and silts from outside sources along the sea bottom on the shelf. These are moved by waves and currents. In this area, they are coming from the north and east toward the south and west.

Relative importance of the different processes that produce these general relationships varies within the area studied. Differences in processes between subareas is discussed below following a description of the sediments. There it is shown how differing processes may produce the same type of lithology.

SEDIMENTS

General Features

The vertical sequence of types of deposits forming at different water depths on the front of the actively building delta corresponds to the stratigraphic sequence making up the completed delta wedge. As the delta builds seaward, sediment characteristics at any particular horizon are incorporated into the wedge and their relative position is maintained as modified by later compaction and structural movements. Characteristics of the sediments are analogous to those of the classic delta sequence consisting of topset, foreset, and bottomset beds. However, no sharp planes of separation exist and initial dips are at very low angles. All available data indicate that this relationship holds around the entire Mississippi Delta.

In general, near the distributary mouths the sediments are largely derived from the river and contain very little marine-derived material. In deeper water farther from the distributary mouths, as the rate of deposition of river sediments decreases, the slower rates of supply of marine-derived material become increasingly important, until, farther out to sea, shells and current-transported sand and silt from outside areas constitute much of the deposited sediment. Several characteristics of the sediments will be described which vary systematically with increasing distance from shore and depth of water along any traverse outward. These characteristics are gross lithology, texture (grain size), coarse fraction composition, and color.

Gross lithology is most complex and variable in the shallow water near the

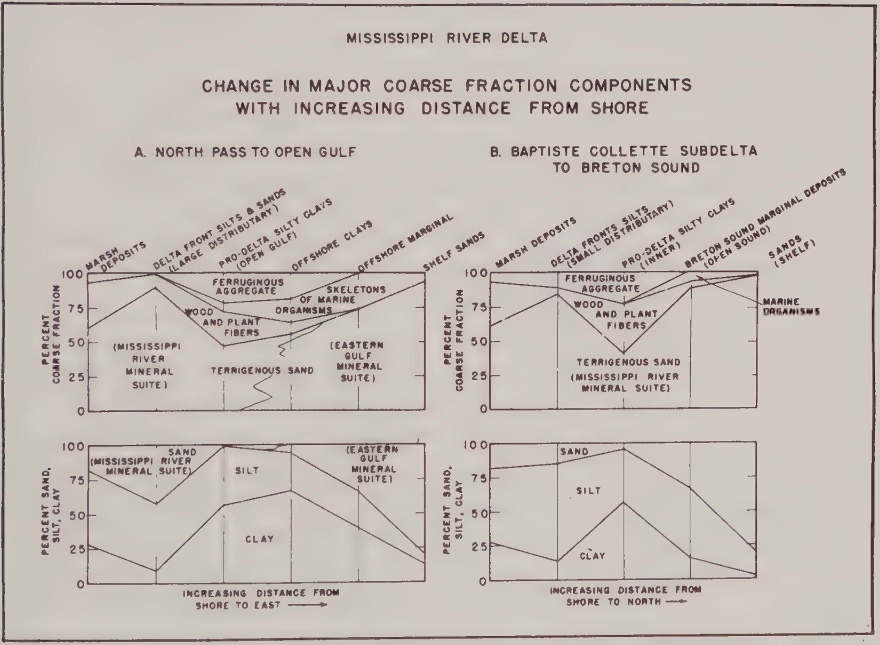

FIG. 3.—Note changes in amounts of sand with increasing distance from the delta. Composition of the sand also changes; terrigenous (land-derived) components decrease, marine-derived components increase, and eastward from North Pass the mineral suite changes.

coast and becomes more uniform and homogeneous with increasing water depth and distance seaward. Near the outer edge of deltaic deposition, lithologic structures change character and gradation into the outlying sands begins. Grain size varies in somewhat the same manner (fig. 3). It generally is coarsest and most variable near the delta shore, becomes finer and more uniform outward at greater depths, reaches a minimum, and with greater distance seaward on the shelf, again becomes variable and coarse until the outlying sands are reached. Within the coarse fraction (fig. 3) the general progression is a decrease in the amounts of terrigenous (detrital) sand to very small percentages of the total deposit. Land-derived woody material also decreases to the eastward paralleling its decrease in suspension shown by Riley (1937). Beyond the sand minimum (which may have considerable areal extent) quantity of detrital sand again increases. Mineralogy and grain size relationships show that this sand is derived from the outlying shelf deposits, however. Remains of marine organisms also become more abundant, increase toward the outer sands, and in some areas, replace woody material. Colors of surface sediments generally vary from yellowish brown or brown near shore through olive gray to light olive gray with increasing distance seaward. Colors below the surface zone also appear to vary systematically from brownish gray near shore through olive gray and grayish black to dark greenish gray and olive gray offshore.

Areas within which these different characteristics are relatively uniform have been mapped as sediment units. The sediment units, in order of seaward occurrence, are called: "delta front silts and sands," "pro-delta silty clay," "offshore clays," "marginal deposits," and "sands." Within the delta itself, lying above the marine sequence, is another sedimentary unit, "marsh deposits." In addition there are deposits exposed which were produced by deposition previous to the present delta cycle. These beds are called "older deposits." The first three of the listed units are the most important in delta growth. They are deposited approximately concentric to the distributary mouths. In general their characteristics depend on distance from source and depth of water. The fourth sediment unit, marginal deposits, as the name suggests, occurs at the outer edge of the delta deposit where river-derived silts and clays are mixed in a transition zone with the bottom sands from outside the delta.

The distribution of these sedimentary units on the eastern side of the Mississippi Delta is shown in figure 1. Boundaries of the units were drawn after study of the core samples. Since changes in sediment character are gradational and only small changes occur in short distances, the exact locations of boundaries must be somewhat arbitrary. The order of discussion of sediment units is from the shore outward (youngest to oldest as they would appear from the top to the base of a section through the completed delta wedge, see fig. 4). Figure 5 is a fence diagram that shows both vertical and lateral relationships between sediment units northeast of the delta.

Description of Sediment Units

Marsh deposits.—Deposits of the marshes (including the natural levees) lie at the top of the completed cycle of delta deposition and are a portion of the topset bed (fig. 1). They are the only deposits in the active delta formed above mean sea level and are deposited under both fresh and brackish water conditions. These beds are built up mainly from deposition of suspended material carried into the marshes during high river stages by overtopping of natural levees and also by growth and subsequent deposition of marsh vegetation. Overtopping of the natural levees during high river stages occurs particularly in conjunction with high tides, because

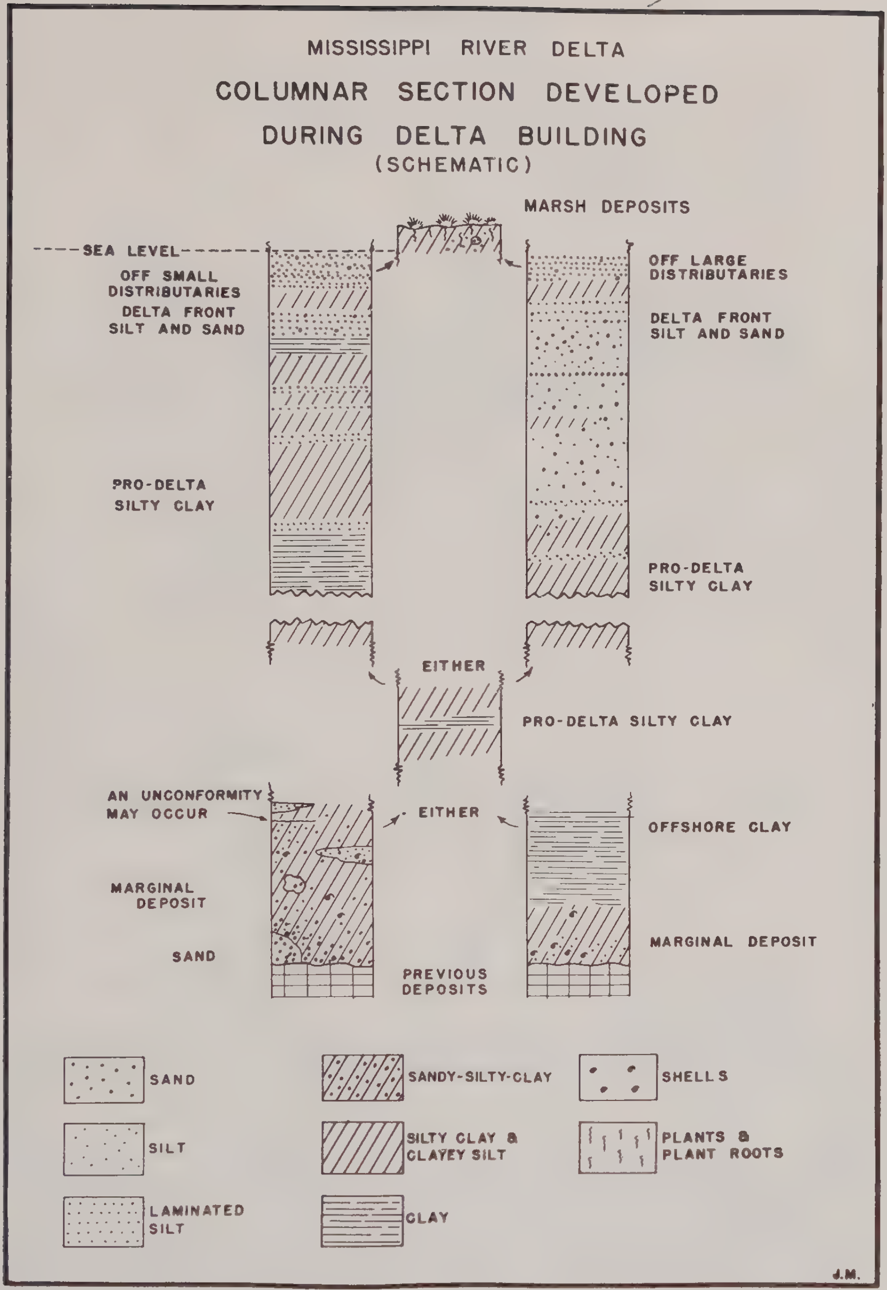
MISSISSIPPI RIVER DELTA
COLUMNAR SECTION DEVELOPED DURING DELTA BUILDING
(SCHEMATIC)
MARSH DEPOSITS
SEA LEVEL
OFF SMALL DISTRIBUTARIES
DELTA FRONT SILT AND SAND
OFF LARGE DISTRIBUTARIES
DELTA FRONT SILT AND SAND
PRO-DELTA SILTY CLAY
PRO-DELTA SILTY CLAY
EITHER
PRO-DELTA SILTY CLAY
AN UNCONFORMITY MAY OCCUR
EITHER
OFFSHORE CLAY
MARGINAL DEPOSIT
SAND
MARGINAL DEPOSIT
PREVIOUS DEPOSITS
SAND
SANDY-SILTY-CLAY
SHELLS
SILT
SILTY CLAY & CLAYEY SILT
PLANTS & PLANT ROOTS
LAMINATED SILT
CLAY
J.M.

FIG. 4.—Shows the vertical distribution of sediment units in the completed delta. Because of areal variations, some differences exist in the vertical sequence from place to place. Either of the sequences may occur at the indicated positions.

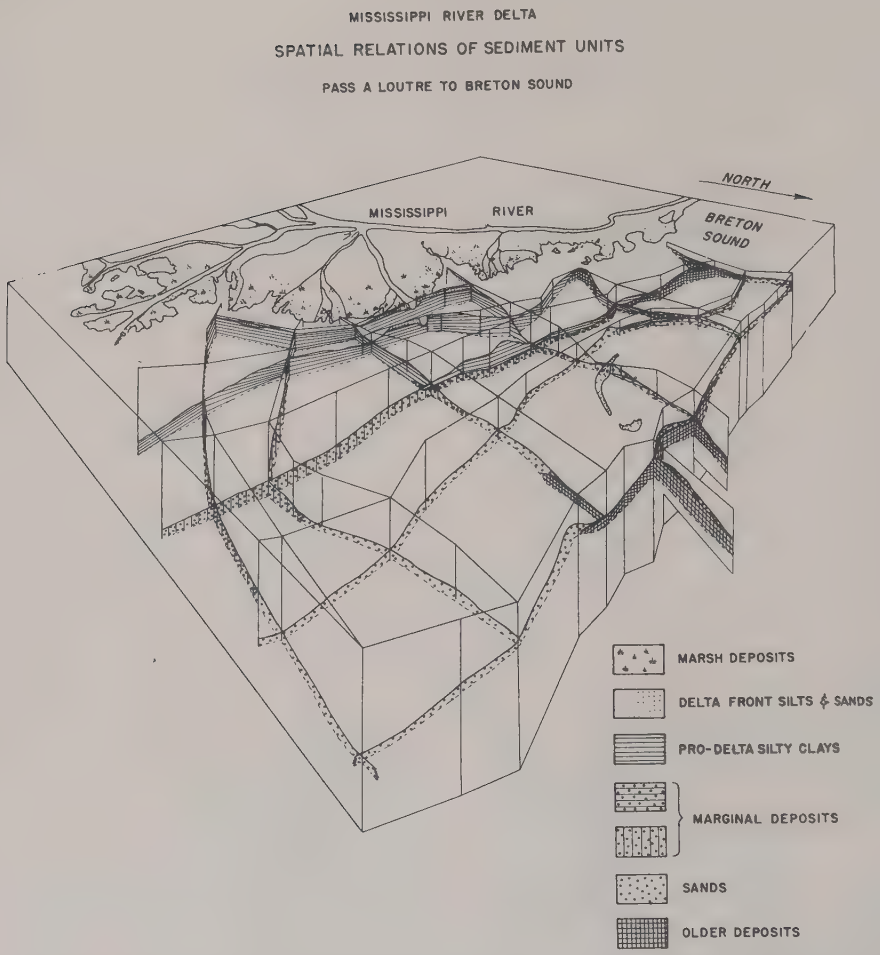
MISSISSIPPI RIVER DELTA
SPATIAL RELATIONS OF SEDIMENT UNITS
PASS A LOUTRE TO BRETON SOUND
MISSISSIPPI RIVER
NORTH
BRETON SOUND
MARSH DEPOSITS
DELTA FRONT SILTS & SANDS
PRO-DELTA SILTY CLAYS
MARGINAL DEPOSITS
SANDS
OLDER DEPOSITS

FIG. 5.—Fence diagram showing three-dimensional relations between sediment units in the inshore portion of the delta area. Marsh deposits lie at the top of the completed sequence.

raising of the sea level partially impounds river-flow causing river level to rise even more. Hurricanes, which may raise sea level several feet around the delta, also cause general flooding of the marshes. Probably a relatively small amount of material is brought in in this manner, however.

Marsh deposits consist principally of clayey silt[3] or silty clay but also contain appreciable quantities of sand (fig. 6). They frequently are heterogeneous in texture, and usually contain many small

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[3] Sand-silt-clay terminology is the system recently suggested by Shepard (see Shepard, F. P. (1954) Nomenclature based on sand-silt-clay ratios: Jour. Sedimentary Petrology, v. 24, fig. 7, p. 157).

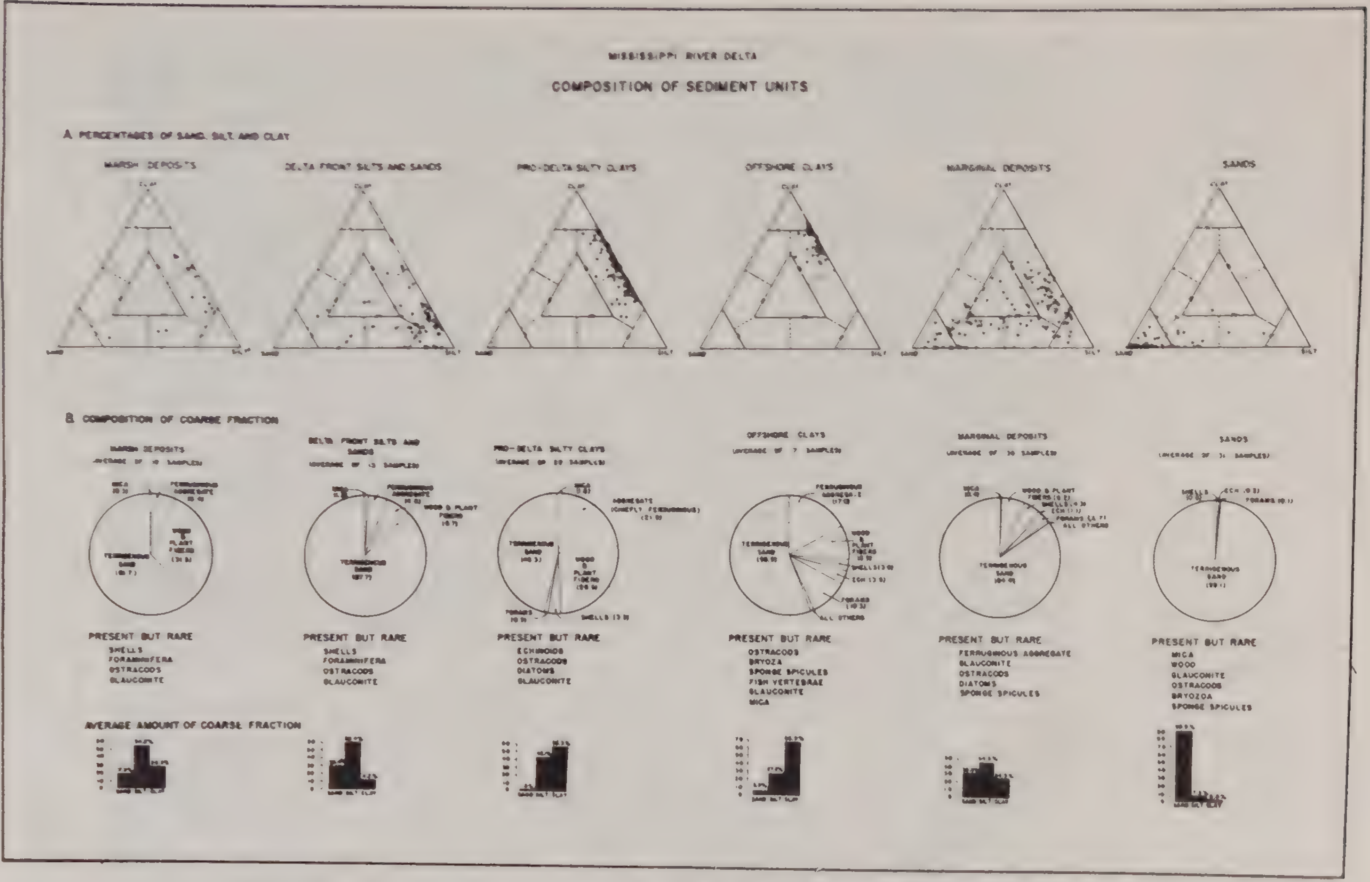

FIG. 6.—Note: Solid black histograms on line three show average sand, silt, and clay contents of the samples analyzed for coarse fraction composition.

lenses of silt or sandy silt near the base of the deposit (fig. 7). They also tend to be somewhat coarser on the low natural levees than in the marsh farther from distributaries. The coarse fraction (sediment coarser than 0.062 mm) contains an abundance of woody material in addition to the detrital sand; shells or shell fragments are rare. In addition to detrital sand and small fragments of plant material, there is an abundance of plants and plant roots buried *in situ* (fig. 7). These larger plant remains bond the deposit into a coherent mat.

In general, marsh deposits are quite thin over the young land surface of the

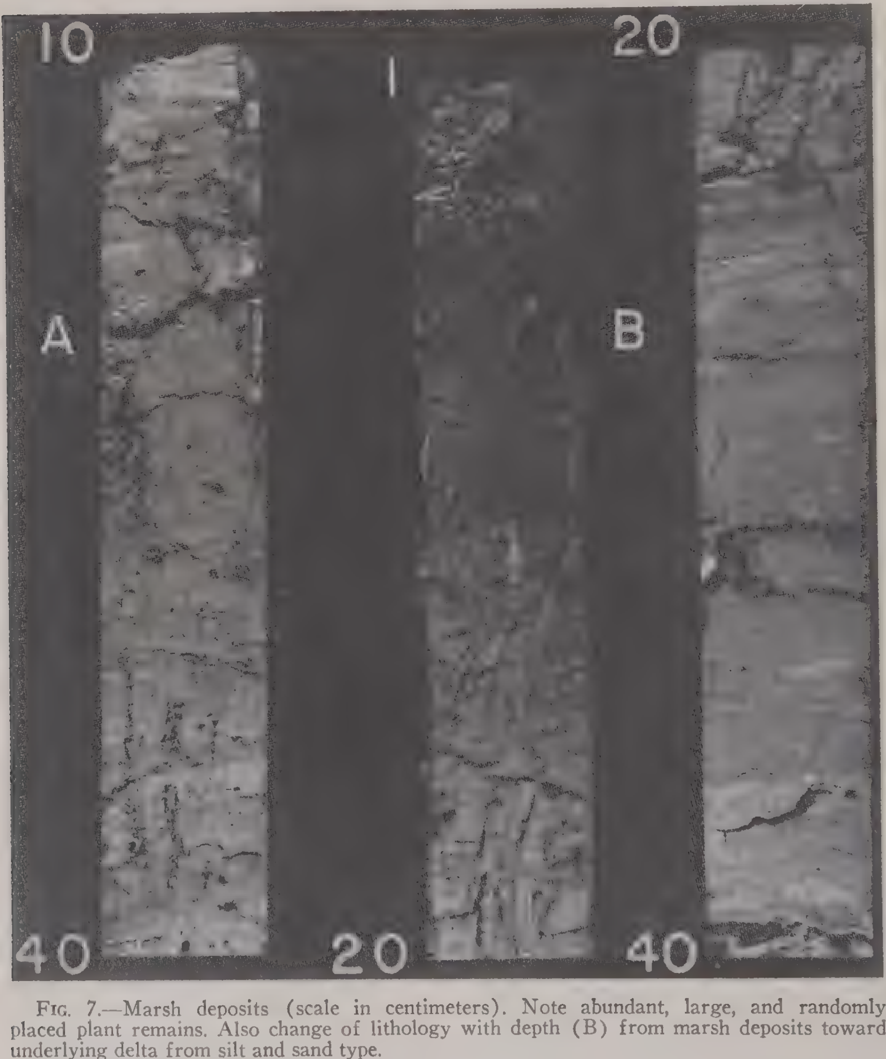

Fig. 7.—Marsh deposits (scale in centimeters). Note abundant, large, and randomly placed plant remains. Also change of lithology with depth (B) from marsh deposits toward underlying delta from silt and sand type.

eastern Mississippi Delta. Natural levees are the thickest parts of the marsh; their height (and thickness) above mean sea level is determined initially by the height of flood waters and by tidal rise. This initial thickness of natural levee deposits, and other parts of the marsh as well, is increased by continued addition of sediment during compaction of underlying beds.

Delta front silts and sands.—Delta front silts and sands occur as a generally continuous deposit of variable thickness seaward of the mouths of the numerous delta distributaries (fig. 1). These deposits are composed almost entirely of river-derived material. There is more silt than sand in the delta front deposits, although the general impression seems to have been that they are mostly sand. The triangle diagram in figure 6 shows that in most of the analyzed samples the sand content is less than 50 percent. Most of the sand present is very fine. In the area of delta front silts and sands shown in figure 1 there are no beaches around the delta.

In all samples, woody material is present and in some it is abundant. Shell fragments, Foraminifera, and ostracods are rare and entirely absent in some samples. Averages of coarse fraction analyses (sediment coarser than 0.062 mm) of thirteen samples showed 87.7 percent terrigenous sand, 6.7 percent wood and plant fibers, and the remainder mostly mica and a ferruginous (limonitic) aggregate of silt and clay which apparently is authigenic and persists even after treatment with sodium hexametaphosphate.

Delta front silts and sands deposited in shallow water, usually off small distributaries, overlie all other marine beds of the delta. They grade downward into both pro-delta silty clays and the silts and sands formed off the major distributaries. For this reason, they are considered part of the delta's topset bed.

The smaller distributaries carry a relatively small amount of river water and sediment and initially discharge their load into very shallow water. The water depths in which silts and sands off small distributaries are being deposited range from a few inches to approximately six feet with an average of three to four feet. Wave and current action continually sort and retransport the material. Cores show that under these conditions, the thin delta front deposits consist mostly of alternating layers of coarser material, well sorted sandy silt, and finer material, silty clay or clayey silt. The coarser layers of sandy silt generally show sorting with the coarsest material at the bottom and an upward gradation to finer material. The individual coarse layers range in thickness mostly from three to 20 cm, but some are thicker. Because of small variations in components or texture, they exhibit in the cores distinct and persistent fine lamination throughout. Some of this fine bedding is horizontal and regular, some is cross bedded, and some is wavy and distorted (fig. 8). The cross bedding occurs in relatively thin subzones (up to two cm thick) with inclinations up to 25 degrees from the horizontal.

The layers of finer material, clayey silt and silty clay, usually are thinner than the sandy silt beds, ranging in thickness from two to 10 cm. The texture of these layers tends to show a systematic change with the finest sediment near the center of the layer. Individual clayey layers often include a few thin beds or lenses of silt. There are also some lenses, composed of fine bits of woody material, with thicknesses from a few millimeters to 50 centimeters. Morgan (1953) called this material "coffee grounds." Locally in the bays scattered oyster or other shells occur at this general horizon.

Cores taken in closely spaced core holes show that the alternating layers of sandy silt and silty clay change in thickness and appearance laterally within short distances. Individual laminations

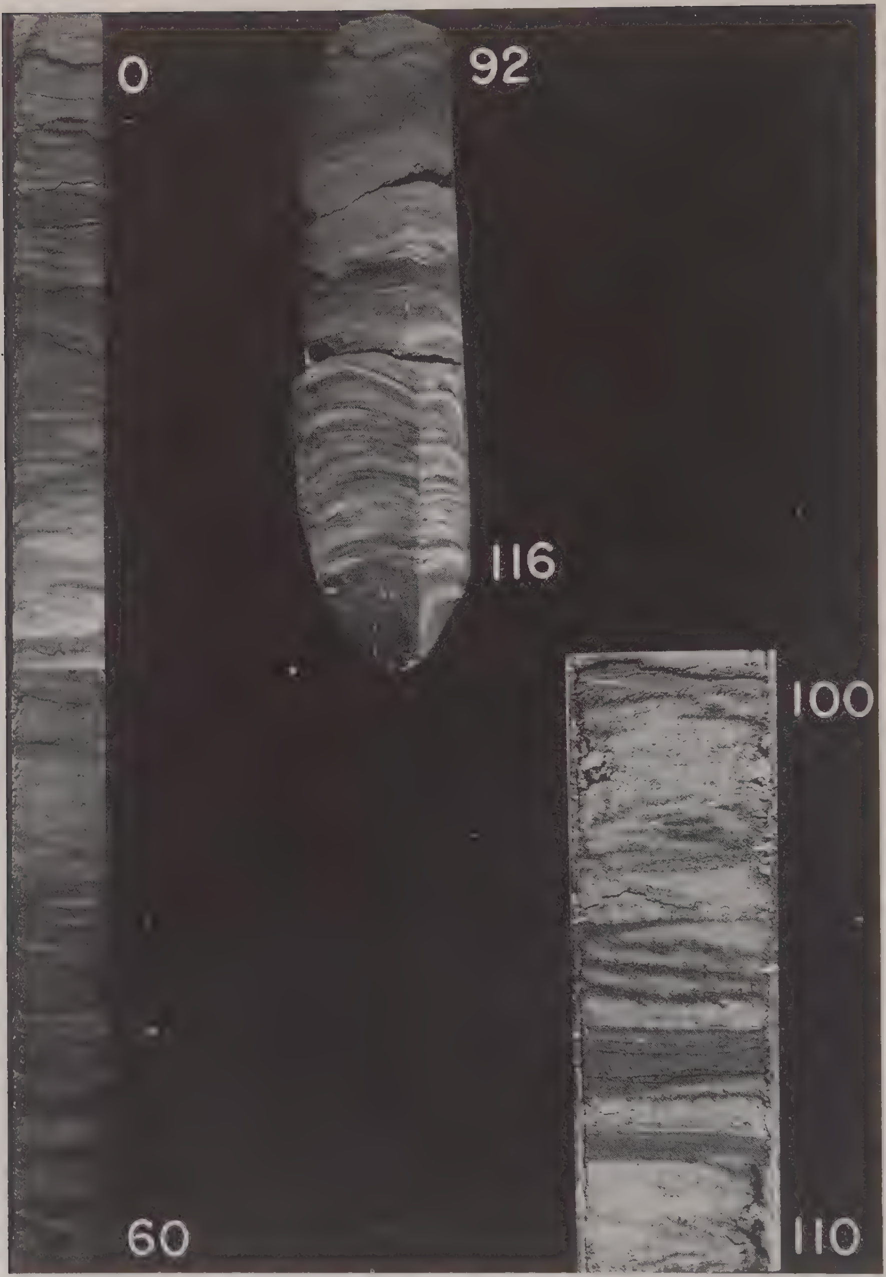

FIG. 8.—Delta front silts and sands (scale in centimeters). Note delicate lamination, small scale cross bedding, and alternating zones of coarse and fine materials (0-60).

do not seem to persist as much as a yard, although the layers can be traced several times this distance. In most cores if the coarser silt layers are thick, the alternating finer clay layers are thin, and where the clayey layers are thick, the silt layers tend to be thin. Despite the lack of areal uniformity in the alternations of silt and clay layers, they appear to have been deposited, at least in some places, in small depositional cycles. These cycles may be related to the annual fluctuations in kind and amount of sediment because of variation in the river discharge, but this record is obscured by the annual wave cycle. The shallow delta front deposits usually contain several superimposed alternations of coarse and fine layers; the range in total thickness is from approximately one to six feet, averaging about four feet thick.

Off the mouths of smaller distributaries, the thin beds of delta front silts and sands grade downward into pro-delta silty clay by progressive increase in thickness of the clayey zones, decrease in thickness of silt zones, and absence of fine lamination in the silts. As the small distributaries continue to build their coalescing deltas seaward, the recently deposited delta front sediments along the channels are eroded so that underlying clays constitute the channel floors.

Delta front silts and sands deposited in deeper water off the mouths of major distributaries underlie a zone of silts and sands of the shallow water type (fig. 4). They are deposited on the steepest seaward slopes of the delta, correspond in some ways to a coarse phase of pro-delta silty clays, and represent a part of the delta's foreset bed system. Because of their relative coarseness and relationship to distributory mouths, however, they are mapped as a unit with the silts and sands of shallow water.

Delta front sediments off the larger distributaries differ in several respects from those formed in shallow water, usually off the small distributaries. They tend to be more massive than those formed in shallow water and to have less sharply defined vertical changes in texture, to be somewhat coarser although less well sorted, and are considerably thicker. They also occupy different positions in the delta wedge, so that they differ in their spatial relations with pro-delta silty clays. The reasons for these differences are that the larger distributaries carry more and coarser sediment, deposit this material at faster rates, and build their parts of the delta into deeper water. The high rate of deposition in deeper water reduces the winnowing and retransporting effects of currents and waves. The sediments are distributed more according to the settling velocities, with coarsest material nearest the channel mouths. Such deposits tend to have fewer laminations and less sharply defined textural changes because they are not washed, sorted, and retransported in shallow water. As these deposits build upward to sea level, however, and the water depth decreases, their characteristics become like those formed off small distributaries. Plate II (detail) shows the relationships between the delta front sediments and pro-delta silty clays.

Sand off the channel mouth is coarsest and best sorted on the crests of the bars where the water is shallow, and it generally becomes progressively finer with increasing depth of water and distance from the channel mouth, both seaward and laterally. The coarsest material is deposited seaward of the bars when the river is in flood stage and fresh water is flowing seaward at all depths in the channels. Delta front samples when the river flow is high range from very fine sand to medium silt size (median diameters 0.12 mm to 0.02 mm). At other seasons samples are finer than this, both upstream and seaward of the bar crests, although bar crest material may be quite coarse at any season.

Both coarse and fine zones occur in the silts and sands off large distributaries. Cores of the coarser zones (sands, silty sands, and sandy silts) show that they are relatively thick and quite homogeneous vertically and textural changes are gradual. The zones of finer texture (clayey silt, silty clay) also may be relatively thick and contain numerous thin layers of silt. Some bedding consisting of one to two cm thick layers of sand or silt may be present. There is very little of the small scale cross bedding and sharply pronounced vertical cyclic variation that was described in similar sediments deposited in shallow water.

Total thickness of the delta front deposits off any large distributory is related to the maximum depths of water in which they were deposited initially. Under existing discharge conditions, the maximum depth at which delta front silts and sands are found is about 60 feet off Southwest Pass, 35 feet off North Pass, and 10 to 12 feet off Main Pass. The depths increase in order of percentage of total river discharge carried by these distributaries. Seaward slopes of the delta front off the distributaries are relatively uniform (concave upward, maximum of about two degrees in 12 to 30 feet of water, decreasing seaward) so that depth limits (and thickness) of the deposits now forming apparently are related principally to distributary discharge (cf. Humphreys and Abbot, 1876; Holle, 1952). This relationship would not hold, of course, if these distributaries were discharging into shallower water.

These deposits remain in the deltaic wedge as elongate sandy masses marking the old courses of large distributaries. The form of delta front silts and sands in cross section perpendicular to their long axes is highly variable. They tend to be deposited symmetrically about the channel mouth, to be widest at the top, and to narrow with increasing depth. Comparisons of old and recent charts show, however, that distributary mouths, uncontrolled by artificial levees, shift from side to side of the stabilized axes of channel elongation. The sandy deposit, therefore, may be convex downward in cross section, relatively flat on top, and be asymmetrical about the channel extension.

Delta front silts and sands off the larger distributaries grade both laterally and downward into pro-delta silty clays. The grain size progressively decreases, and the lithology becomes less complex and variable.

Much of the material referred to by Russell and Russell (1939) as "natural levee deposits" and by Fisk (1952) and Fisk, McFarlan, *et al* (1954) as "sand fingers" or "bar sands" is deposited in this delta front environment. As demonstrated by South and Southwest Passes (fig. 1), a large distributary tends to build seaward in a straight line. As it moves ahead, it erodes its channel into the coarser material previously deposited, and wherever the distributary channel is deep enough, it will erode through the recent delta front deposits. However, the sediment in these deposits is not all clean sand but contains much silt and clay both in the sandy zones and in the alternating finer-grained zones (fig. 6).

Pro-delta silty clays.—On the east side of the Mississippi Delta, pro-delta silty clays (pro: in front of, before) are being deposited in a continuous belt varying in width from about one to ten miles (fig. 1). The belt extends from lower Breton Sound seaward to depths as great as 30 fathoms. Similar silty clays occur off Southwest Pass and must surround the entire active delta. They correspond to the foreset beds of classic delta descriptions, and probably are the "soft muds" of earlier workers (Shaw, 1913).

Pro-delta silty clays consist typically of homogeneous silty clay or clayey silt with a trace of sand-sized particles. A glance at the histogram in figure 6 shows that on the average they are about half silt and half clay. Actual percentages in an average of the samples analyzed were sand 1.6 percent, silt 42.1 percent, and clay 56.3 percent. The coarse fraction (coarser than 0.062 mm) contained the following kinds of material: terrigenous sand 45.3 percent, wood and plant fibres 26.5 percent, aggregates (mostly ferruginous) 21.9 percent, shells and shell fragments 3.3 percent, Foraminifera 0.9 percent, and mica 1.6 percent. In addition there were a few echinoid spines, ostracod valves, and diatom frustules. At and near the surface the silty clays are soft and fluid, but they stiffen with increasing depth of burial. Colors (based on comparison with the Rock Color Chart, Goddard, 1951) of the surface material near shore are brown or yellowish brown and become brownish gray with depth in the core. Farther offshore, surface colors are olive gray to light olive gray and at depth in the core are dark gray, olive black, or black. Still farther seaward color at and beneath the surface is olive gray.

The silty clays are deposited mainly by almost continuous settling of suspended material from the water above. Sediment-charged river water flowing out over gulf water beneath gradually loses its remaining load consisting of silt, clay, a little sand, and bits of wood and plants. This occurs during lateral distribution of river water and while mixing with salt water proceeds. Distribution and character of silty clays, therefore, are controlled largely by the currents distributing river water and by distance from the sources. Currents principally responsible for this distribution are tidal currents, wind-driven currents, regional semi-permanent currents, and currents in and around the distributary mouths due to conserved momentum of river water, mixing of fresh and salt water, and hydraulic head. Off the large distributaries turbidity currents or slumping probably also occur.

The pro-delta silty clays are a quite homogeneous body of mixed silt and clay. They are mostly clayey silt on the shoreward side and silty clay to seaward. In shallow water the homogeneity is interrupted by thin beds of slightly coarser material, either clean silt or clayey silt, which appear in core sections as continuous laminae or lenses (fig. 9). These laminae normally are two to three mm thick, but vary from a fraction of a millimeter to over one centimeter. The bounding surfaces of the laminae are smooth and sharp, and individual laminae have relatively constant thickness. These coarser silt beds are rarely themselves laminated, and no regular textural gradations, such as "graded bedding," were detected in the microscopic examinations of core sections. The thin silt beds occur singly or in sets, where they are separated by variable thicknesses of silty clay. Cores taken in holes only three feet apart show that sets of laminae usually can be correlated, but individual laminae can not.

These laminations are best developed in shallower water and apparently are formed by the winnowing effect of wave action. They become progressively rarer, thinner, and less distinct in deeper water, until at depths of 20 to 25 fathoms laminations of any kind are rare in pro-delta silty clays.

As in all sediment units around the delta, there is a progressive gradation in the material from near shore out to deeper water. On any single traverse outward from shore, sand and silt content of samples decreases and clay content increases. Where sand has not been transported into the area from an outside source, sand content in the silty clays is less than one percent within a mile of the one fathom curve (fig. 1). An exception to this is off Southwest Pass where sand persists somewhat farther seaward because of the large volume of sediment and water carried by that distributary.

Thickness of pro-delta silty clays depends on the depth of water into which the delta is built. Their total thickness increases from 15 feet or less near Main Pass in shallow water to about 175 feet near North Pass in deeper water. Silty clays make up the large bulk of the delta

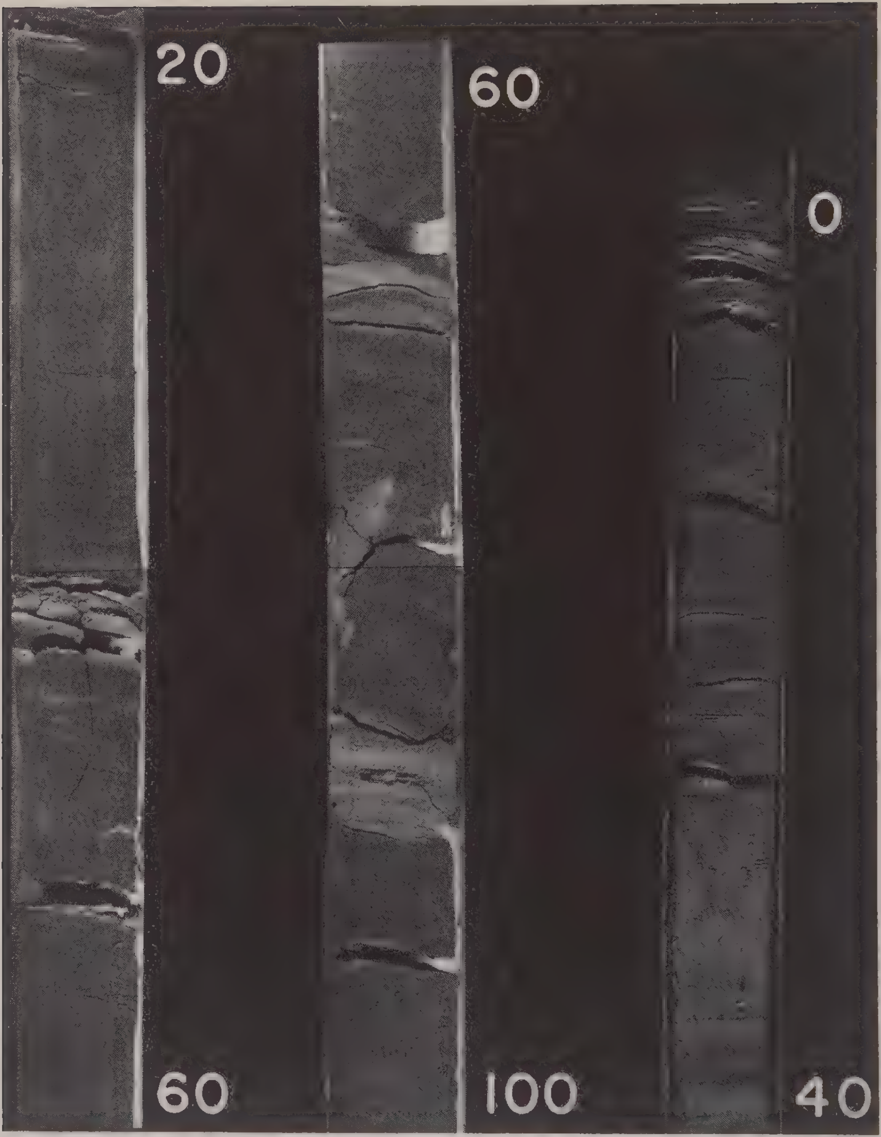

FIG. 9.—Pro-delta silty clays (scale in centimeters). Note zones of thin silt laminae separated by thicker zones of smooth silty clay.

wedge and thicken seaward as the delta is extended into deeper water.

Pro-delta silty clays normally grade outward and downward into offshore clays or marginal deposits (figs. 1, 4). However, as the delta grew northeast in shallow water it decreased the size of the channel between Main Pass and Breton Island (fig. 1). This accelerated tidal currents in the channel and an area of scour and erosion rather than deposition was created temporarily. Some previous deposits have been removed and pro-delta silty clays are advancing seaward directly over older deposits. Position of the small unconformity is shown in figure 4. The lower part of the silty clays above this unconformity contains laminae of coarser material, sand and shell fragments, derived from adjacent older beds. These abnormal laminae are coarsest, thickest, and most numerous at the base. The sediments grade upward into typical pro-delta silty clays.

Offshore clays.—On the east side of the Mississippi Delta, offshore clays are being deposited in an area up to 20 miles wide (fig. 1). They are found mostly in water deeper than 20 to 25 fathoms. It is not known yet with any accuracy how far out to sea or to what maximum depth south of the delta the offshore clays extend, but it is probable they go into depths of at least 500 to 600 fathoms on the continental slope. They are formed by the normal settling of fine river-derived clay and silt onto the ocean floor. To this material are added shells of marine organisms and sand or other sediment transported by currents from outside sources. Offshore clays are equivalent to the classical bottomset beds of delta literature.

The triangle diagram of offshore clay samples (fig. 6) shows that all the samples analyzed contained some silt and most of them a little sand. The average of samples analyzed for coarse fractions was clay 66.9 percent, silt 27.2 percent, and sand 5.9 percent. The increase in percent of sand over that found in pro-delta silty clays (1.6 percent) is from samples collected near the outer margins of offshore clays and is due to sand transported in from outside sources by currents. Coarse fraction analyses show much more material from marine organisms than is found in sedimentary units closer to shore. Average percentages are: terrigenous sand 55.9 percent, ferruginous aggregates of clay and silt particles (authigenic) 17.0 percent, wood and plant fibers 8.9 percent, Foraminifera 10.3 percent, echinoids 3.6 percent, shells and shell fragments 3.0 percent, and all other material 1.3 percent.

These clays are the finest-grained sediments found in the active delta. They are smooth, homogeneous, and relatively stiff (fig. 10). Lamination of any sort is rare and if present, consists of thin concen-

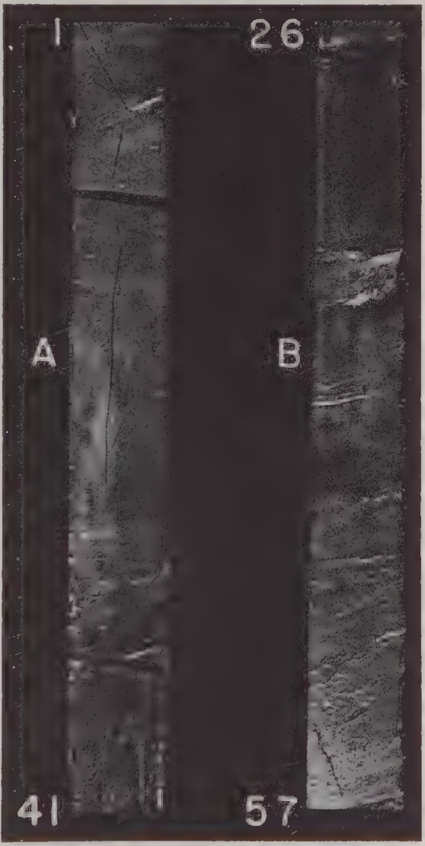

FIG. 10.—Offshore clay (scale in centimeters). Texture is uniform and fine-grained.

trations of shells, echinoid plates, other shell fragments, and some silt and sand. Color of the clay is light olive gray at the surface, and changes to olive gray or dark greenish gray within three to 10 cm into the deposit. Landward, the clays grade into the silty clays of the advancing delta. Offshore clays overlie marginal deposits and grade laterally into them northward and eastward (figs. 1, 4) where clay is mixed with sediment from outside sources.

Where measurements have been possible, offshore clays on the east side of the Mississippi Delta are thin. Eleven miles east of Pass a Loutre Light on the landward edge of the area in which they occur, cores showed only seven feet of the clay on top of marginal deposits. Cores taken still farther east found the clay even thinner. Other cores taken northeast of Pass a Loutre showed the clay somewhat thicker. Variations in thickness are controlled by distance from shore, prevailing directions of currents carrying suspended sediment (Scruton and Moore, 1953), and irregularities of the original topography of the sea floor.

Marginal deposits.—The name "marginal deposits" is applied to the mass of more heterogeneous sediment which occurs on the shelf surrounding the advancing delta embankment. These deposits floor most of Breton Sound and form an almost continuous belt between the silty clays and clays and the sands lying farther seaward (fig. 1).

The material in marginal deposits ranges in size from sand to silty clay and varies both vertically and laterally. the sand is brought in from nearby sandy bottoms, silt and clay are derived mainly from the Mississippi River, so that there are two sources of clastic sediments for these beds. In general the fine and coarse components of marginal deposits also seem to be introduced at different times and by different processes. The fine-grained components are mainly the result of relatively constant settling from suspension, whereas the coarse materials are introduced periodically along and near the bottom during more extreme conditions.

The most characteristic feature of marginal deposits is the presence of curious pockets, lumps, or irregular lenses which give a mottled appearance to core sections (fig. 11). These lumps or pockets are of coarse material in a fine matrix or fine material in a coarse matrix. Normally they are about one to ½ cm in diameter, but they range up to about four cm in diameter. Texture of the lumps and pockets may differ sharply from the matrix or there may be intergradation. Various activities of burrowing organisms apparently produce these features. The deposits also often consist of a more or less homogeneous mixture of sand and clay with only a little silt. Irregular variations in the proportions of sand, silt, and clay and in the degree of mixing cause a vaguely mottled or zoned appearance. In some marginal areas there are also thin irregular beds of sand containing many shell fragments. Color of these deposits usually is light olive gray at the surface and olive gray at depth.

The triangle diagram of figure 6 shows that the percentages of sand, silt, and clay vary greatly between individual samples. An average of 35 samples was sand 30.6 percent, silt 44.5 percent, and clay 24.9 percent. The coarse fraction (coarser than 0.062 mm) is mostly detrital sand. However, remains of marine organisms are common, and bits of wood and plant fibers are common near the delta but rare to the east (fig. 3). Shells and woody material usually are scattered through the sediment, but may be concentrated in lenses or layers. Marginal deposits east of the dashed line in figure 1 contain Eastern Gulf sand. West of this line they contain Mississippi River type sand.

Marginal deposits show a general gradation in character outward from shore. Textures generally become coarser. The

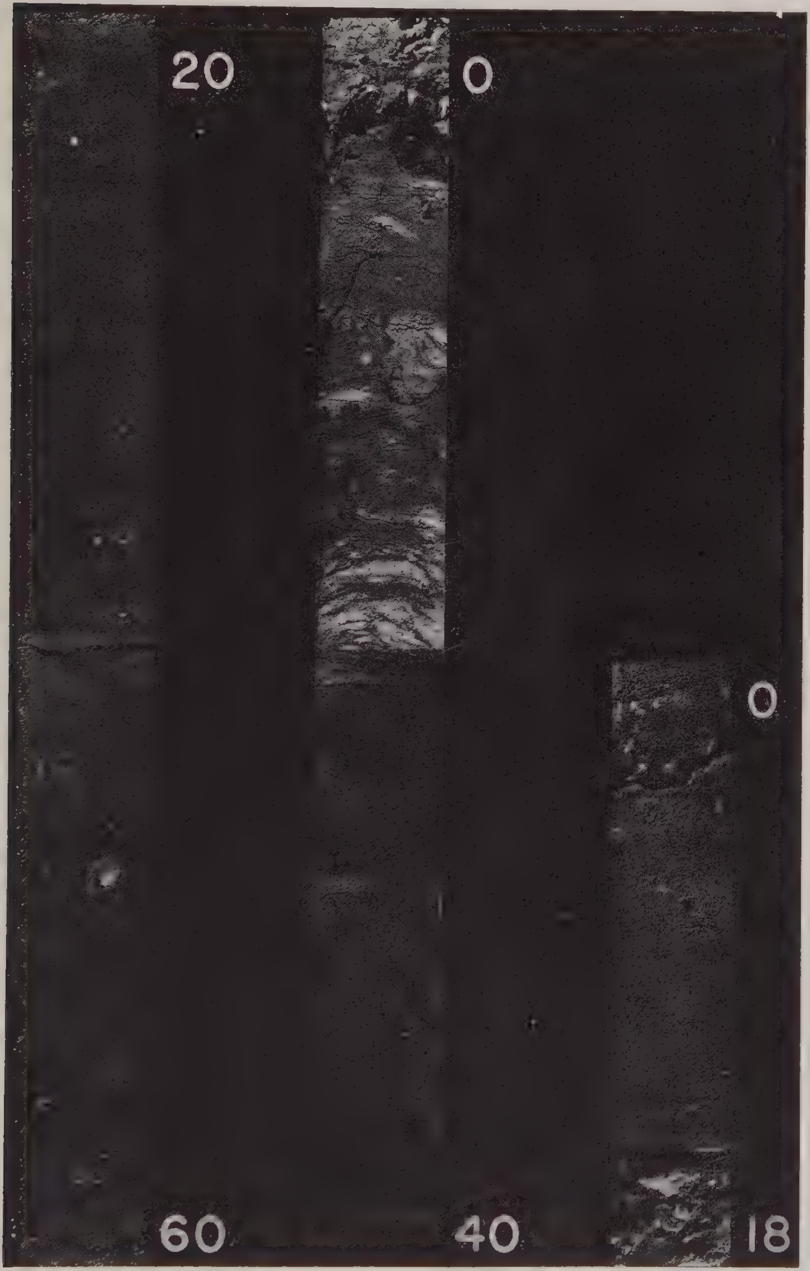

FIG. 11.—Marginal deposits (scale in centimeters). Note sandy lumps and lenses, irregular and indefinite stratification, indistinct contacts, random variations of texture, and shells.

general outward textural gradation is shown in the sand-silt-clay triangle of figure 6 by a continuous series from silty clay or clayey silt to sand. Within this general outward gradation many exceptions occur, however, and there usually is a "patchy" distribution of different kinds of sediment. Thus, silty sand may occur in an area that is mainly clayey silt. Average grain size of the sand fraction also increases outward in some areas. An increase in shell material usually accompanies the increase in detrital sand.

Lithologic structures also change outward. Development of pockets, lumps, and irregular lenses is poor near shore, but they became prominent seaward as sand content increases. Thickness of sandy zones and the number of irregular sandy bodies increase at the expense of silty clay. In core samples this is the way the outward textural gradation into sand occurs.

Marginal deposits have been penetrated completely in Breton Sound and the eastern offshore area. The minimum thickness in Breton Sound is approximately one foot, and lithology of underlying deposits indicates they probably are related to the St. Bernard Subdelta. In the eastern offshore area a minimum thickness of about two feet was found and the underlying material was shelf sand. Maximum thickness of marginal deposits of the present delta cycle is unknown but probably is not great.

Long cores in marginal deposits show the general tendency is for sand content to increase with depth in the deposit. Marginal deposits grade downward into sand by the same changes that occur in the horizontal, that is, by an increase in numbers, size, or thickness of sandy lumps, pockets, layers, and lenses. Because the sand is derived from adjacent sand bodies, thickness and character of marginal deposits may give an index to the proximity, character, and thickness of these sands.

Sands.—The widespread sands shown on figure 1 are not being brought in by the present Mississippi River. Sands of Mississippi River type (Goldstein, 1942) have been concentrated, principally from older delta deposits, by marine erosion and winnowing on the shallow Gulf floor. During and following winnowing, this sand has been transported by waves and currents, concentrated in some places, and distributed thinly over other large areas. Sand of the Eastern Gulf province also is widespread. This sand has remained unburied since the postglacial sea level rise as described previously. Mineralogy of Eastern Gulf type sand seems to show that its ultimate source was the Southern Appalachian metamorphic belt (Goldstein, 1942).

RATE OF DEPOSITION

Depositional environments of the Mississippi Delta are controlled by: (1) sources of sediments, (2) effective processes, and (3) rates of deposition. Rate of deposition is a property of the environment that depends, to some degree, on the other two. However, rate of deposition exerts primary control on sediments by selecting or limiting the effective processes.

The rate of deposition of any one kind of material can determine or limit the amounts, kinds, or characteristics of other materials that are deposited. For example, a high rate of clay deposition may prohibit the local existence of all but a few certain kinds of organisms, make it impossible for wave action to develop clean beach sands, or for slow chemical processes to occur at the sediment-water interface. By influencing biological activity and chemical reactions, these limits also may affect both the kind and extent of later physical and chemical diagenetic modifications.

Depositional environments change outward from the Mississippi Delta, and the changes produce the different belts of sediments that encircle the delta. Rate

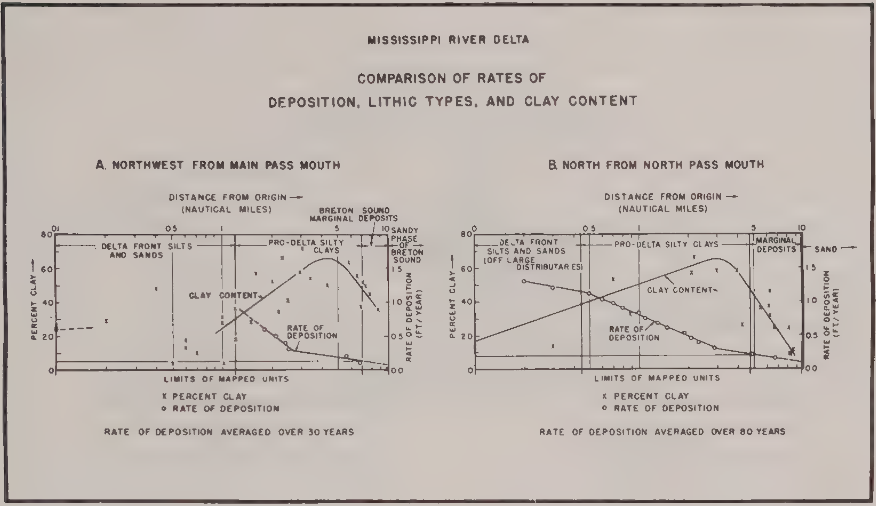

FIG. 12.—Profiles are along corresponding lines A and B of figure 1. Curves and mapped limits of sediment units show the similarity of the sequence of lithologic types, rates of deposition, and clay contents *outward* from the delta between profiles. "Outcrop" widths of the units, and the distances they extend seaward vary *around* the delta from profile to profile, however.

of deposition is one of the factors that changes outward and exerts much control over the sediments.

Close approximations to rates of deposition have been obtained in the Mississippi Delta by comparing depth charts constructed at different times (depth changes between surveys being converted to rates of deposition expressed as feet per year). The shorter the period of time represented between depth charts, the more real are the rates of deposition. Two curves of rate of deposition plotted against distance from the nearest principal distributary mouth are shown in figure 12, and are along corresponding lines A and B of figure 1. Limitations of survery coverage made it necessary to use different periods of time. Boundaries of sediment units and clay content of surface samples along the lines of section also are shown.

Curves A and B of figure 12 are similar in shape and somewhat different in slope except in the areas of delta front silts and sands. Within the area of pro-delta silty clays, rates of deposition are very high and decrease rapidly with increasing distance from distributary mouths. Depositional rates of pro-delta silty clays on these traverses range from greater than one foot per year to about 0.15 feet per year. Rates of deposition of marginal deposits are slower (less than about 0.15 feet per year), but also are uniform between these two regions. The curves of clay content also show similarities, increasing with increasing distance from distributary mouths to maxima which coincide approximately with breaks in the rate of deposition curves. These similarities between curves show there is a distribution of rate of deposition around the delta that corresponds to the distribution of sediment types.

Figure 13 generalizes on these findings. As the delta advances seaward, the rate of deposition at any particular point increases with approach of the

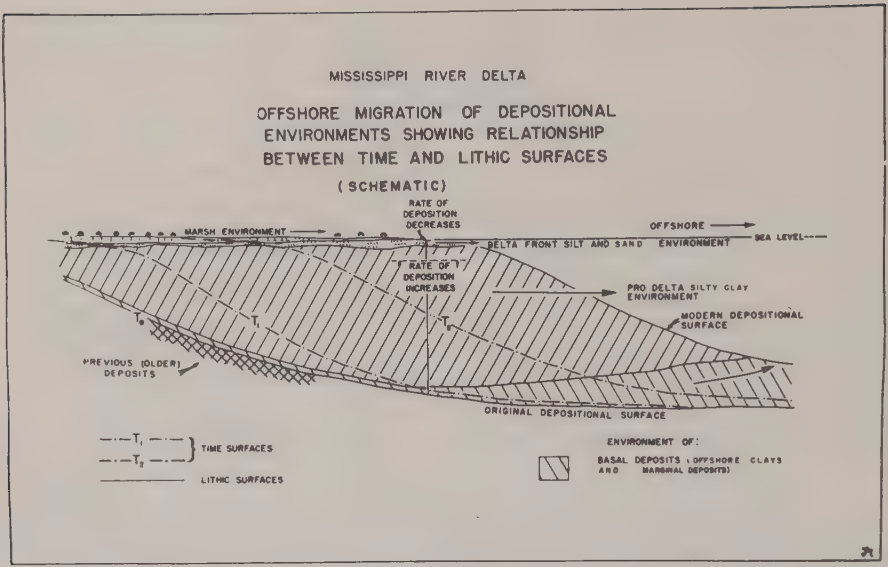
MISSISSIPPI RIVER DELTA
OFFSHORE MIGRATION OF DEPOSITIONAL ENVIRONMENTS SHOWING RELATIONSHIP BETWEEN TIME AND LITHIC SURFACES
(SCHEMATIC)
RATE OF DEPOSITION DECREASES
MARSH ENVIRONMENT
OFFSHORE
SEA LEVEL
DELTA FRONT SILT AND SAND ENVIRONMENT
RATE OF DEPOSITION INCREASES
PRO DELTA SILTY CLAY ENVIRONMENT
MODERN DEPOSITIONAL SURFACE
T0
T1
T2
PREVIOUS (OLDER) DEPOSITS
ORIGINAL DEPOSITIONAL SURFACE
T1
T2
TIME SURFACES
LITHIC SURFACES
ENVIRONMENT OF:
BASAL DEPOSITS (OFFSHORE CLAYS AND MARGINAL DEPOSITS)

Fig. 13.—Deposition on the delta's seaward slope builds the bottom toward sea level and causes seaward migration of the different depositional environments so that the sediment units they produce are extended. Rate of deposition in any area increases as the shore builds out until the depth of water is relatively shallow (shown schematically by the dashed horizontal line). Deposition continues after this, but the rate decreases and is very low in the marshes.

distributary mouths. The rate rises to a maximum determined by location with respect to the large distributaries. The water shoals also, so that winnowing by wave and current action becomes more effective. At some depth of water (also determined partly by distance from large distributaries) winnowing begins to decrease the rate of deposition, and continued building of the delta toward sea level increases the effectiveness of wave and current action. This phase is recorded by the lithology of the upper part of pro-delta silty clays and by delta front silts and sands formed in shallow water. The rate of deposition continues to decrease after formation of the marsh and may be very slow in the higher marshes or behind well developed natural levees. Decrease in rate of deposition of clastic material in the marsh results in the greater relative importance of vegetation in the sediments. Figure 13 also shows the relationships between time and lithic surfaces in the delta.

LOCAL RELATIONS BETWEEN SOURCES, PROCESSES, AND RATES OF DEPOSITION

Although there is a similar distribution of sediments and rate of deposition *outward from* the delta and although processes are generally similar around the delta, there are local variations in processes or in relative effectiveness of processes *around* the delta. These differences in processes or their effectiveness around the delta produce the differences in depth of water or distance from sources at which similar sediments occur (fig. 1).

Conditions along three traverses outward from shore are described below to show how the basic processes are modified and how the similar sediments are being produced. These traverses are (fig. 1): (1) eastward from North Pass mouth, (2) seaward along line B, and (3) northwest along line A.

The outward sequence of deposits off the Mississippi Delta is best illustrated eastward from North Pass mouth (fig. 1). The gradation of sediments is being produced through a broad range of depth and distance from sources in a series of environments in which relatively gradual variations of water properties and effective physical processes occur. In this area residual river velocity, wind, and semi-permanent currents are the agents principally responsible for sediment distribution. These agents cause fluctuations in direction and distance of transportation. Numerous small valleys and depressions on the seaward slope of the delta wedge suggest also that turbidity currents or slumping occur intermittently. Increasing distance from river source and fluctuating direction of transportation produce decreasing rates of clastic sediment supply seaward and greater relative abundance of organic remains. Depth also increases and results in lessened wave action and more uniform bottom conditions. Marginal deposits on the shelf east of the delta are forming through slow supply of river-derived sediments because of distance and direction from source, slow supply of Eastern Gulf or Mississippi type sand because of water depth, and a slow continuing supply of shells. Tidal currents seem to have little net effect because of low relief of shelf topography, although inshore they aid in supplying sediment from the Cubits Gap and Baptiste Collette distributary systems.

Northward from the Cubits Gap distributary system towards Gosier Island (just west of line B, fig. 1), the outward sequence of deposits, although similar to the eastward series, is compressed in length and does not include typical offshore clays. Delta front silts and sands are typical of the deposits off small distributaries forming under conditions of decreasing rate of deposition in shoaling water. Northward in deeper water semi-permanent currents have little direct effect, but reversing tidal currents, wind currents, and residual river flow are important. Tidal currents flowing to and fro between the open Gulf and Breton Sound are accelerated because of constriction between the deltaic embankment and the submarine extension of the Chandeleur Arc. Higher speed of tidal currents has a three-fold effect, each tending to reduce the rate of deposition of river-derived sediment and to increase seaward change of sediment properties. First, these currents restrict seaward migration of the surface turbid zone by influencing its direction of movement. In this way they reduce the supply of fine sediments to the bottom. Second, tidal currents also tend to prevent deposition of fine-grained material which is supplied, and finally, they spread laterally the sand thrown into suspension by waves on the adjacent shallow sand bottom. The effects of wind currents and residual river flow (similar in this area to the two-layer estuarine circulation such as described by Ketchum, 1953) are additive to tidal currents and generally increase or decrease tidal current speeds, depending on instantaneous conditions. The combined effect of these currents, together with a relatively high rate of supply of sand derived from the Chandeleur area to the north, is producing a narrow zone of pro-delta silty clay and a relatively wide and thick marginal deposit. Increased speed of tidal currents toward the northwest because of greater constriction of the channel prevents sedimentation at present directly off Main Pass mouth, and the currents have scoured into pre-existing deposits (fig. 1).

Along line A of figure 1 deposits and conditions near the delta generally are similar to those just described, although tidal effects are altered somewhat by topography. In the Breton Sound marginal area (west and northwest of

Breton Island), however, the processes are different. Tidal currents and surface flow from the Cubits Gap and Baptiste Collette systems carry suspended sediment into Breton Sound, particularly during late spring and early summer. Current speeds decrease in the open sound and generally are weak, and the suspended sediment settles. Intermittent strong northerly winds commence in September, continue through April, and produce high waves in the shallow sound. These waves resuspend much of the previously introduced fine sediment. Currents, also produced by these winds, offset normal tidal oscillations, flow seaward continously from the sound during the storms, and remove most of the fine resuspended material gained during previous periods of calm. Sand and silt are derived locally from the islands and from reworking of the shallowest areas by waves and also are distributed under these extreme wind conditions.

FORMATION OF MINOR LITHOLOGIC STRUCTURES

Similarities and differences between these three areas and other data suggest origins for the characteristic bedding and other minor lithologic structures of the sediment units (figs. 7–11). Structures of shallow water delta front silts and sands seem to be produced by winnowing and bottom transportation by waves, tidal currents, and high river discharge, and by variations of supply due to seasonal river fluctuations. The delicate laminae are preserved, despite decreasing rate of deposition, because the environment is unfavorable to organisms. Thicker vertical variations in texture in delta front silts and sands off large distributaries seem to be caused by seasonal discharge variations in river flow, but the fine laminae, like those in pro-delta silty clays, seem to be the result of periodic winnowing by waves and lateral transportation by tidal or other currents. Rate of deposition is high, organisms are scarce, and laminae are not destroyed after formation. Prominent lamination generally is absent in the deeper parts of pro-delta silty clays and in offshore clays because water depth prohibits extensive winnowing by waves and the sediment is uniformly fine-grained. Typical structures of marginal deposits apparently are produced by burrowing organisms. The various conditions of origin of marginal deposits all combine to produce a slow rate of deposition. This permits the relatively abundant faunas that live on them to destroy most of the laminations formed by periodic introduction of coarse sediment or by winnowing.

SUMMARY

Recent studies of the Mississippi Delta make it possible to better describe many features of the sediments and the general character of some of the fundamental sedimentary processes. In some cases, the relationships between these two can be shown. The processes are complex and usually are difficult to isolate, so that their detailed definitions and relationships with the sediments require much more work in the area.

Environmental factors and processes in the Mississippi Delta determine the kinds and amounts of materials that are supplied and deposited in a given time. The depositional rate of any one kind of sediment also influences the amounts and kinds of all other materials that are deposited. Amounts and kinds of materials in the sediments also influence which post-depositional chemical modifications can occur. Therefore, total rate of deposition and rate of deposition of each sediment component are derived environmental factors of great importance in controlling petrography.

Environments in the active Mississippi Delta generally produce a rate of deposition that is greater than the rate of subsidence. They also simultaneously produce a wide range of types of sediments that bear definite spatial and lithologic relationships to each other.

Environments migrate seaward because of delta growth (a form of marine regression), and develop distinct but interrelated sedimentary units of large lateral extent.

All of the structural elements of classic delta description are present on the east side of the modern Mississippi Delta. Bottomset beds are represented by offshore clays, foreset beds by pro-delta silty clays and delta front silts and sands off large distributaries, and topset beds by marsh deposits and shallow water delta front silts and sands. There are differences between model lake deltas and the large marine delta, however, that are due largely to marine influences, textures of sediments, and scale of the phenomenon. Main differences on the continental shelf that result from marine processes and density differences are: (1) the presence of multi-source deposits underlying bottomset beds, (2) much smaller seaward slope of foreset beds on the delta face than the 10 degrees to 25 degrees found in lakes, and (3) the absence in some places of one of the structural elements.

Knowledge of the processes and the types of sediments they produce permits interpretation of the flux of environments represented by a vertical section in more ancient deposits. Thickness of the total section originally measured the water depth into which the delta advanced, but this later has been modified by compaction and subsidence. A thick section of clay low in sand content suggests the position of these beds is a considerable distance from a sand body, but a thick sandy sequence of either marginal or pro-delta silty clay type deposits suggests nearness to equally thick sand bodies formed during the delta's constructional cycle. Because of the source of sand for the outlying sand bodies, active delta growth in the immediate area is not necessary for their formation. These beds can form during long periods of delta inactivity and later may be buried by a local renewal of delta building.

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ERUPTION OF BÁRCENA[1] VOLCANO, SAN BENEDICTO IS., MEXICO[2]

By Adrian F. Richards[3] and Robert S. Dietz[4]

Introduction

The first historic pumice eruption in the eastern Pacific Ocean basin occurred on August 1, 1952, when a new volcano was born on San Benedicto Island off the west coast of Mexico. San Benedicto, one of the four islands of the remote, uninhabited, oceanic Revillagigedo group, is located 218 nautical miles south of the southern tip of Baja California and approximately 1000 miles south-southeast of Los Angeles (Plate I). The only previous report of a volcanic eruption in the eastern Pacific north of the equatorial Galápagos Islands was in 1848 when Lt. J. W. Revere (1849; 1947) on the U.S.S. PORTSMOUTH, witnessed an eruption of Socorro Island, 28 miles south of San Benedicto. Revere dismisses the eruption briefly, consequently it is inferred that he may have observed only strong fumarolic activity or a cloud cap. However, ash beds partially cover dead tree stumps on the southeastern part of Socorro indicating activity in the not too distant past.

The initial study of the San Benedicto eruption through October 1952, was made by Dietz, who then left for a year in Japan. The investigations subsequent to October were made by Richards.

This paper is preliminary in scope and consists primarily of an outline of observations of the events in the birth and development of Bárcena Volcano; no attempt has been made to describe in detail many of the observations or to report laboratory work.

Formation of the Cone

The birth of Bárcena was witnessed by men of the tuna clipper CHALLENGER, and related to the authors by Joseph da Luz, Master of the CHALLENGER, and Robert Petrie, who took a series of photographs of the eruption. According to these men, at 0745 on August 1, 1952, the CHALLENGER was fishing about two miles west of San Benedicto Island when, without previous warning, a thin pencil-like wisp of

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[1] The late Teredo Flores, Director of the Instituto de Geologia of the Universidad Nacional, Mexico, in 1953 named this volcano Bárcena in honor of Mariano Bárcena, Mexico's foremost geologist in the late 19th century. Bárcena Volcano had been previously known as "Boquerón" or "Big Mouth."

[2] Contribution from Scripps Institution of Oceanography, New Series No. 793.

[3] Scripps Institution of Oceanography, La Jolla, California.

[4] U.S. Navy Electronics Laboratory, San Diego, California.

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white steam was seen to rise silently skyward from behind the southern extension of Herrera Crater. By the time the steam column reached the 975-foot elevation of the Ash Heap, the highest structure on the island at that time, very dark ash-charged steam was observed to shoot rapidly skyward and quickly spread out laterally, producing an effect similar to the "base-surge" of an atomic blast (Plates III-IV). This illustration shows that the dark steam and ash column had already ascended to over 7000 feet and nearly obscured the three-mile-long island. Twenty minutes after the first wisp of steam had appeared, the sky became dark due to pumiceous dust and ash in the air; the ocean, which had previously been clear and blue, was observed to become turbid with suspended pumice; and, as the CHALLENGER left the island at top speed, dust and ash fell on the deck of the ship. Surprisingly, Petrie reports that no noises, attributable to a volcanic source, were heard aboard the ship. Evidently bombs or blocks also were ejected from the new volcano because splashes in the sea were noticed to the southwest of the island. After leaving San Benedicto the CHALLENGER steamed south to Socorro Island and three days later traveled to Roca Partida, 75 miles west of San Benedicto. The ash column was clearly seen by day and flashes of light illuminated the sky the first night the ship was at Socorro.

The next report of the eruption was obtained from Chester Blasko of the tuna clipper INTREPID, which arrived at San Benedicto on August 12th, after having passed through floating pumice rafts commencing 120 miles north of the island. Blasko observed that the sea was "milky" with suspended pumice in a 15-mile radius around the island and that Bárcena was in a state of continuous, violent eruption. In the ship's fish-spotting Piper Cub, he flew near the volcano taking aerial Kodachrome motion pictures which show that on the 12th the pyroclastic cone was already higher than the 975-foot elevation of the Ash Heap. From this comparison it is apparent that Bárcena built up from an estimated 200 feet above sea level to an elevation of approximately 1200 feet in 12 days or less. The motion pictures also show evidence of strong vulcanian eruptions with the discharge of eruption products closely resembling *nuées ardentes* from the eastern or lower rim of the volcano. In addition Blasko reported that "rocks as large as the galley" were ejected an estimated 2800 feet above the crater and fell into the cone burying themselves. A continuous thunder-like roar was heard over the noise of the plane's motor.

No further information was learned regarding the new volcano until September 12th, when an Air Force B-29 flight to Bárcena was arranged with the 55th Strategic Reconnaissance Squadron. Ruy Finch, Grant Anderson, and Dietz participated on the flight. During the 1½ hours in the vicinity of San Benedicto Island, eruptions of yellowish-grey ash and steam cauliflower clouds were observed approximately every twenty minutes with a duration of five to ten minutes (Plate V). Volcanic noises, if present, could not be heard above the roar of the plane's engines. Although the crater was filled with steam between explosions, on the windward side it was possible to see part way down into it. The inside was scarred by large slides and slumps. No blocks or bombs were observed to be ejected during the visit and none were seen on the cone, which appeared to be entirely composed of ash. Comparison of the photographs taken on the flight with the motion pictures taken by Blasko on August 12th indicated that the cone had changed little during the previous month. Evidently the major cone building phase had ceased about August 12th. On San Benedicto Island north of Bárcena it was noted that rudimentary drainage had become established.

A second B-29 flight was made to Bárcena eight days later on September 20th, with Howel Williams, Ernest Boldrick and Dietz participating. No explosions were seen, or sounds heard, during the 1½ hours the volcano was circled. The relative absence of eruption clouds permitted clear visibility of the island and photographs were taken from 500 to 5000 feet. In the throat of Bárcena Crater steam issued from around a plug of congealed lava. When the plane flew low over the crater through this steam, a slight odor of H_2S was noticed. On the exterior of Bárcena, parallel furrows originating at the low, northeastern side of the crater rim and running straight toward the base were observed. It seems likely that the furrows may have formed from the erosion effect of *nuées ardentes* or ash avalanches. The ash cover of the island had been further eroded by heavy rains between the 12th and the 20th and an incipient drainage pattern had become established (Plate VI). Because of a notable lack of reports on the new volcano from the tuna fishermen in the vicinity it appears probable that Bárcena continued to be relatively inactive until early November. Apparently the plug of congealed lava, which effectively capped the magma conduit in the crater, prevented the release of gas until additional hydrostatic pressure was able to build up, resulting in the November-February activity.

Extrusion of the Crater Lava

On November 13, Manuel Neves, Jr., Master of the CONSTITUTION, sent the first of a series of radio messages on the 13th and 14th to the Scripps Institution of Oceanography of the University of California reporting that Bárcena was again active. Neves stated that a red glare was reflected from low clouds and visible 40 miles away from San Benedicto Island. Light colored steam, with little ash, was ejected at five-minute intervals and a low rumbling sound was heard as each puff of steam ascended above the crater rim on the 14th.

On the 15th a Navy PBM flight was made to the volcano with Douglas Inman, James Snodgrass, and Richards participating. Bárcena Crater, estimated in September to be 700 feet deep and 2,000 feet wide at the rim, appeared half filled with viscous lava that exhibited no daylight incandescence (Plate VII). Crater gas eruptions were infrequent during the hour spent circling the volcano and puffs of steam were observed to rise only a few hundred feet above the crater rim. At the eastern base of Bárcena a very narrow beach was seen for the first time since August, when the volcano had built out to sea an estimated 1500 feet from the old shoreline of the island.

George Zeluff, Master of the PARAMOUNT, radioed the Scripps Institution on the 19th that volcanic activity had increased. Two types of eruptions were noted from the ship's fish-spotting plane. Major eruptions, which started and stopped abruptly, were of ash and steam, with a 45-minute periodicity and a duration of 40 seconds. Minor eruptions, which started and stopped diffusely, had a two and one-half-minute periodicity, a duration of 12–17 seconds, and evidently consisted only of steam, no grey discoloration being visible. At night red glowing rocks were seen ejected several hundred feet above the crater rim. They appeared to fall back into the crater. According to Capt. Perriera, STAR OF THE SEA, essentially the same activity as described by Zeluff in November was witnessed on December 4th.

Formation of the Lava Delta

About 2 p.m. on December 8th a small landslide, noticed by men on several tuna clippers and reported to one of the authors by Capt. Perriera and Manuel Silva of the STAR OF THE SEA, originated in the ash sea cliff 60 feet above sea level at the eastern base of Bárcena. At 9 p.m. a viscous lava was seen to extrude slowly from a small fissure in the cliff at the position of the slide. According to Capt. da Luz of the CHALLENGER, by 8 or 9 a.m. on December 9th the lava had flowed down the sea cliff, across the 200-foot beach, and had reached the sea.

Lewis Walker and Richards arrived at San Benedicto on the yacht OBSERVER, belonging to Woodrow Krieger, at 4 p.m. on the 9th. Measurements by radar, made by Capt. Charles Zamora, and sextant angles after the OBSERVER was anchored 2700 feet from the sea cliff behind the new lava flow, indicated that the lava had advanced 900 feet from the sea cliff in less than 21 hours. The new flow resembled a "delta" and is shown in Plate VIII, which was taken from the fish-spotting plane of the SOUTHERN QUEEN. The flight was kindly made available by John Rippo, Jr., Master of the SOUTHERN QUEEN. According to radar measurements made by Capt. Zamora between 6 p.m. on the 9th and 6 p.m. on the 10th the block lava flow advanced 250 feet seaward. On the 11th the lava delta was measured to be 1200 feet wide. It averaged 70 feet above sea level and had a marginal slope of 14°. The maximum height of the fissure had increased from 60 to nearly 200 feet above sea level. Also on the 11th the lava south of the fissure advanced a measured 40 feet in 12 hours. Above the fissure the crater rim faulted and dropped 15 feet vertically, probably shortly after the lava was extruded at the base of the cone. The resulting graben had a horizontal length of nearly 1000 feet. Minor vertical fractures developed *en échelon* between the lateral edges of the graben and the fissure over 1000 feet below the rim. The ash and cinder core of Bárcena was found to have a relatively uniform external slope of 33°.

Compared with photographs taken on the November flight the interior of the crater (Plate IX) appeared different when inspected on the 9th. Consequently it seems likely that additional lava was extruded into the crater after November 15th. The lava appeared to be in the shape of a roughly circular biscuit, which was later found to be 1350 feet wide by photogrammetry. In the center of the biscuit, surrounded by a moat-like depression, there was a circular area of incandescent lava, later found to be 450 feet wide. Steam eruptions, with a slight odor of SO_2 but without noticeable H_2S, originated from the southwestern side of the central moat-like depression with a periodicity slightly less frequent than described by Zeluff on November 19th (Plate IX). The steam clouds rose only a few hundred feet above the crater rim. Approximately every hour, abruptly starting, vigorous eruptions of dark steam and ash originated from a small orifice at the center of the incandescent lava. The gas pressure was low compared to the activity prior to September 20th. The eruption column, consisting of small cauliflower clouds, ascended to approximately 3,000 feet, where prevailing winds flattened the top of the column. Except for a continuous jet airplane-like roar of steam escaping from the numerous crater fumaroles, all eruptions occurred without warning sounds. On the western, windward, side of the crater, the outer wall of the lava biscuit was approximately 50 feet high and brightly colored with yellow sulfurous compounds.

At daybreak on December 12th the eruption of a small non-incandescent gravity cloud or ash avalanche was witnessed from the beach 2100 feet south of the lava delta. It appeared to pour over the crater rim, and then it swept down the eastern flank of the volcano and finally traveled out to sea over the delta. According to Capt. Perriera of the STAR OF THE SEA, who witnessed the spectacle from about two to three miles east of Bárcena, the portion of the eruption cloud that descended spread out laterally and quickly covered all but the extremities of the three-mile-long island. Shortly afterwards a muddy rain, which lasted for 20 minutes, fell from the eruption cloud and the eruptive activity of Bárcena increased to a continuous discharge of grey steam and ash. On the 13th, the day after Walker and Richards had left the Island, John Zolezzi, Master of the ST. MARY, radioed that the crater discharge of steam and ash was still continuing unabated. No further reports were received until January when the CAPE BEVERLY visited San Benedicto Island on the 5th and 12th.

Paul Lynn, Master of the CAPE BEVERLY, reported that on the 5th he heard an intermittent low-frequency rumbling when his ship was abeam and 1500 feet east of the lava delta fissure. According to Lynn, steam and ash were apparently discharged almost continuously from the crater during both visits. His descriptions of the eruptions, however, indicated that the activity was less intense than when the volcano was observed on December 12–13. The lava fissure was seen to glow more brightly on the 5th than on the 12th, perhaps the first sign that the flow of lava into the delta was decreasing.

San Benedicto was visited on February 27th by the clipper COLUMBUS, according to Capt. Edward Mitchell. R. H. Morton took four photographs from this ship which show that the lava delta had greatly increased in size since December. His photographs also show that steam issued from localized areas on the seaward margin of the flow, indicating that a few tongues of lava were probably still advancing seaward. Eruptions of light colored ejecta occurred intermittently from the crater ascending to approximately 2500 feet. This is the last report of an eruption of steam and ash from Bárcena Crater.

The Fumarolic Phase

In March San Benedicto Island was visited twice by Bayard Brattstrom, Homer Dana and Richards aboard the PAOLINA T of the Scripps Institution, Robert Newbegin, Master. The only observable signs of continued volcanic activity in Bárcena Crater were two large fumaroles in the extreme southeast side of the crater, and innumerable small fumaroles in the crater lava. All the fumaroles observed produced superheated steam. The lava surface had cooled sufficiently to be walked on. The center of the lava inside the moat-like depression, which had been incandescent in December, had subsided, probably due to magma withdrawal, and in place of the small orifice seen in December there was an inverted cone-shaped pit estimated to be over 50 feet deep.

The lava delta appeared essentially unchanged compared to Morton's February photographs. Since no marginal steam or other signs of growth were evident it was concluded that growth probably ceased by the end of February. The bulk of the flow was still too hot to be traversed except at the margin. Locally steam was emitted from the cooling lava, especially at the embayments between tongue-shaped flows. Horizontal projection of altimetry measurements indicated that the average delta height was about 120 feet above sea level. Based on soundings made on the OBSERVER three months previously it is estimated that nearly half of the volume of lava in the delta may be below sea level.

Between April and September, 1953, four Navy P4Y photographic flights were made to San Benedicto Island to investigate erosional changes and to study underwater volcanic acoustics. James Snodgrass and Richards accompanied the flights. Plate X, taken on the May flight, illustrates the island essentially as it appeared in March. From the mosaic the lava delta flow was found to have a maximum width of 1400 yards and extend 700 yards seaward from the ash sea cliff of Bárcena.

The northern half of San Benedicto Island was explored in November, 1953, when the Scripps Institution's CREST, Laurence Davis, Master, visited San Benedicto and Socorro Islands for a week. Some of the erosional gullies in the ash cover of south Herrera Crater were found to be over 15 feet deep and the underlying vegetation and soil still had not been exposed. North of Hererra the ash cover had been in large part eroded off the pre-Bárcena surface exposing dead buried vegetation and the skeletons of birds caught by the August 1 eruption. The ash cover at the extreme north end of San Benedicto is believed to have been at least several feet thick after the initial eruptive phase of Bárcena. Additional investigations concerning the effects of the volcanic activity on the plants and animals and other observations are partially described in: *The Islas Revillagigedo Investigation of November, 1953* (unpublished manuscript).

Preliminary study indicates that the lava and ejecta of Bárcena Volcano cannot be simply classified. The range is from trachyte to andesite. According to Williams (1952) the refractive index about

1.505, of the glass in the pumice suggests a material of rhyolite or dacite composition. However this index is for the most silicic, lightest color, pumice. Less silicic, dark color, pumice has a higher index.

Geological Setting of Bárcena

San Benedicto rises from a depth of 1800 fathoms to an elevation of 1,250 feet so that it has a total relief of 12,000 feet. It is the easternmost of the four islands of the Revillagigedo Group—a roughly east-west chain of volcanoes rising from the deep sea floor. Actually, Clarion, Roca Partida, and San Benedicto form a straight line trending about 15° north of each but Socorro is offset to the south so that the overall trend averages east-west. No additional submerged members of this island group are known but the region is poorly sounded.

In an east-west direction, these islands line up with the trans-Mexico volcanic trend of Orizaba, Popocatepetl-Ixtacihautl, Parícutin, and Colima—a trend exceptional in that it is not oriented parallel with a continental margin or along an arcuate structure. The 400-mile stretch of deep sea floor which separates the island from the mainland has numerous irregularities of moderate relief but there is no clear evidence of any topographic connection.

Menard (in press) considers the Revillagigedo Islands to lie along a major fracture zone in the earth's crust which he terms the "Clarion Fracture Zone." His zone begins with the trans-Mexico trend, includes the Revillagigedo Islands, and extends westward along a great circle path for another 1,700 miles. This westward extension is established on the basis of troughs, asymmetrical ridges, and seamounts over a 60-mile-wide band.

Volcanism probably has progressed from west to east in the Revillagigedo group. Clarion is apparently the oldest, being relatively deeply dissected and having a moderately developed shelf and some fringing coral growth. The shelf-break takes place at 75 fathoms which suggests that lowered Pleistocene sea level has contributed to its development if the concept of shelf origin of Dietz and Menard (1951) is correct. Roca Partida consists of only a small volcanic rock protruding above the surface. A shelf about 300 yards wide and 80 fathoms deep surrounds the rock indicating that it is the remnant of a once somewhat larger island which is now almost completely destroyed by wave attack. Socorro is essentially a slightly dissected dormant volcano, Mt. Evermann, and there appears to be only minor shelf development around the island. As noted above, it is uncertain whether this island erupted in 1848 but, in any event, there is still fumarolic activity and the freshness of some of the ash beds and volcanic flows suggests that activity has occurred within the past few hundred years. San Benedicto, is, of course, the site of the most recent activity and has essentially no shelf except in a limited area at the northeastern end, suggesting that it is the youngest.

This eastward progression of volcanism has taken place elsewhere among the Pacific Basin linear chains of volcanic islands. The Hawaiian Islands are the best example for here all of the leeward islands have been reduced to coral reefs and all present activity is confined to the easternmost island of Hawaii. In the western Caroline Islands, all of the islands have been reduced to coral reefs excepting Truk, Ponape, and Kusaie, which are located at the eastern end of the group and appear to be progressively younger in the order named. The pattern of eastern migration also seems to apply to the Society Islands.

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ILLUSTRATIONS

PLATE I

Location of the Revillagigedo Islands.

PLATE II

The Ash Heap in 1925 from Herrera Crater. The "X" marks the approximate site of the eruption. Note vegetation in foreground. (California Academy of Sciences photograph).

PLATE III

Initial volcanic eruption of August 1, 1952, viewed from two miles west of the island. Southern extension of Herrera Crater in front of eruption column; the Ash Heap to the right. (Robert Petrie photograph).

PLATE IV

A few minutes later. (Robert Petrie photograph).

PLATE V

Bárcena Volcano, September 12 from the east. A portion of Herrera Crater can be seen to the right of the volcano. (Official photograph, U. S. Navy).

PLATE VI

San Benedicto Island on September 20 from the west. From left to right: Herrera Crater and buried southern extension, Bárcena Volcano, and southern remnant of the Ash Heap. (Official photograph, U. S. Navy).

PLATE VII

Bárcena Volcano, November 15. The crater is half-filled with a viscous lava. (Official photograph, U. S. Navy).

PLATE VIII

Lava "delta" and fissure in the eastern base of Bárcena, December 11. Below the fissure the lava is approximately 70 feet above sea level. (A. F. Richards photograph).

PLATE IX

Panorama of Bárcena Crater from the western side, December 10. Steam eruption originating in the inner moat-like depression. The crater wall in the background is approximately 250 feet above the lava flow. (L. W. Walker photograph).

PLATE X

San Benedicto Island. Two large fumaroles are located in the lower left of the crater. The white area in Herrera Crater, to the right of Bárcena Volcano, is a dry lake bed. The lake formed in September 1952, is north to the upper right hand corner of the photograph. (Official photograph, U. S. Navy).

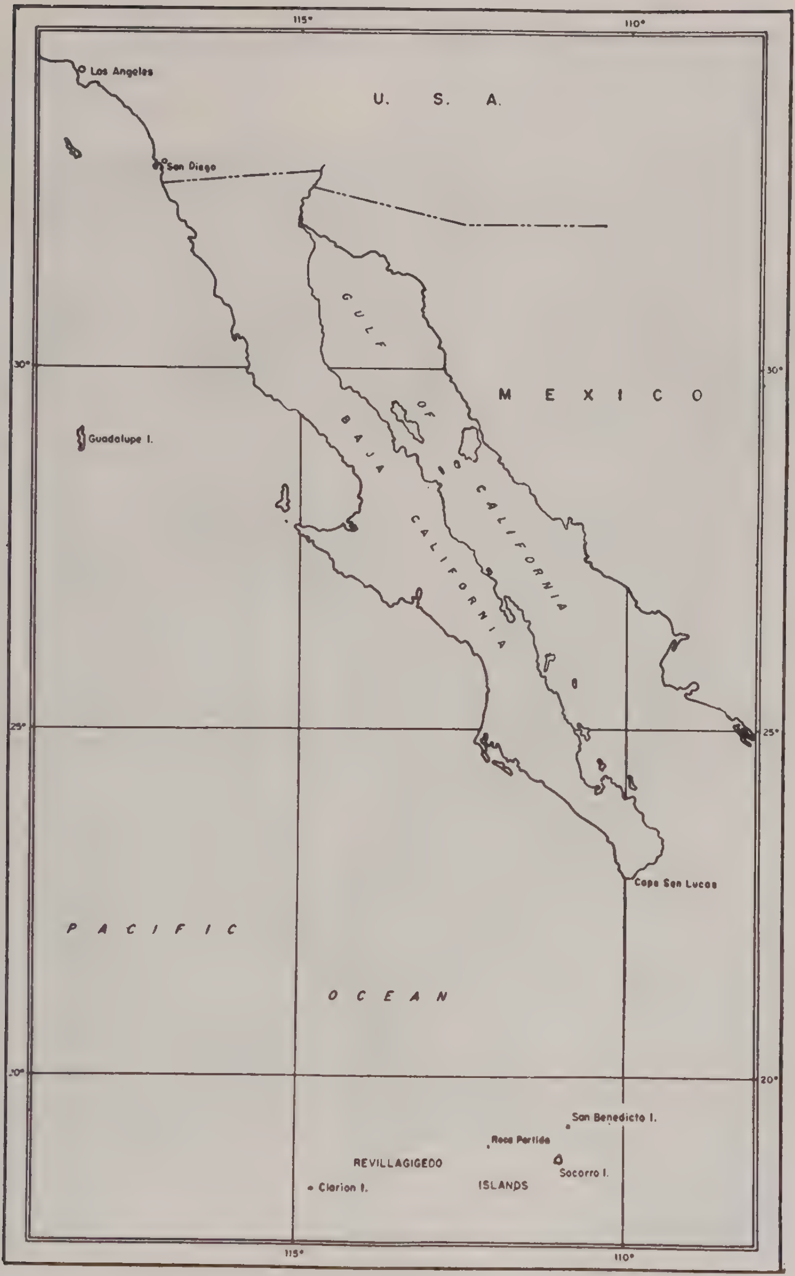
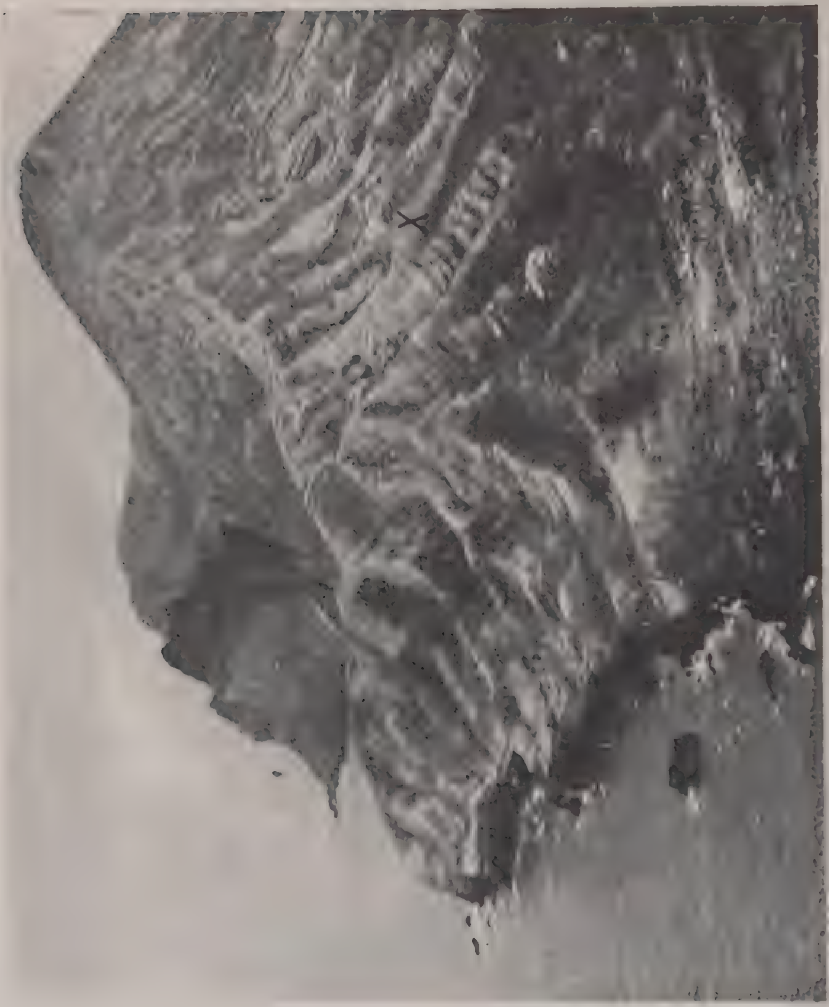

115°
110°
Los Angeles
U. S. A.
San Diego
GULF OF CALIFORNIA
30°
MEXICO
Guadalupe I.
BAJA CALIFORNIA
25°
Cape San Lucas
PACIFIC OCEAN
20°
San Benedicto I.
Roca Partida
REVILLAGIGEDO ISLANDS
Socorro I.
Clarion I.
115°
110°

PLATE I



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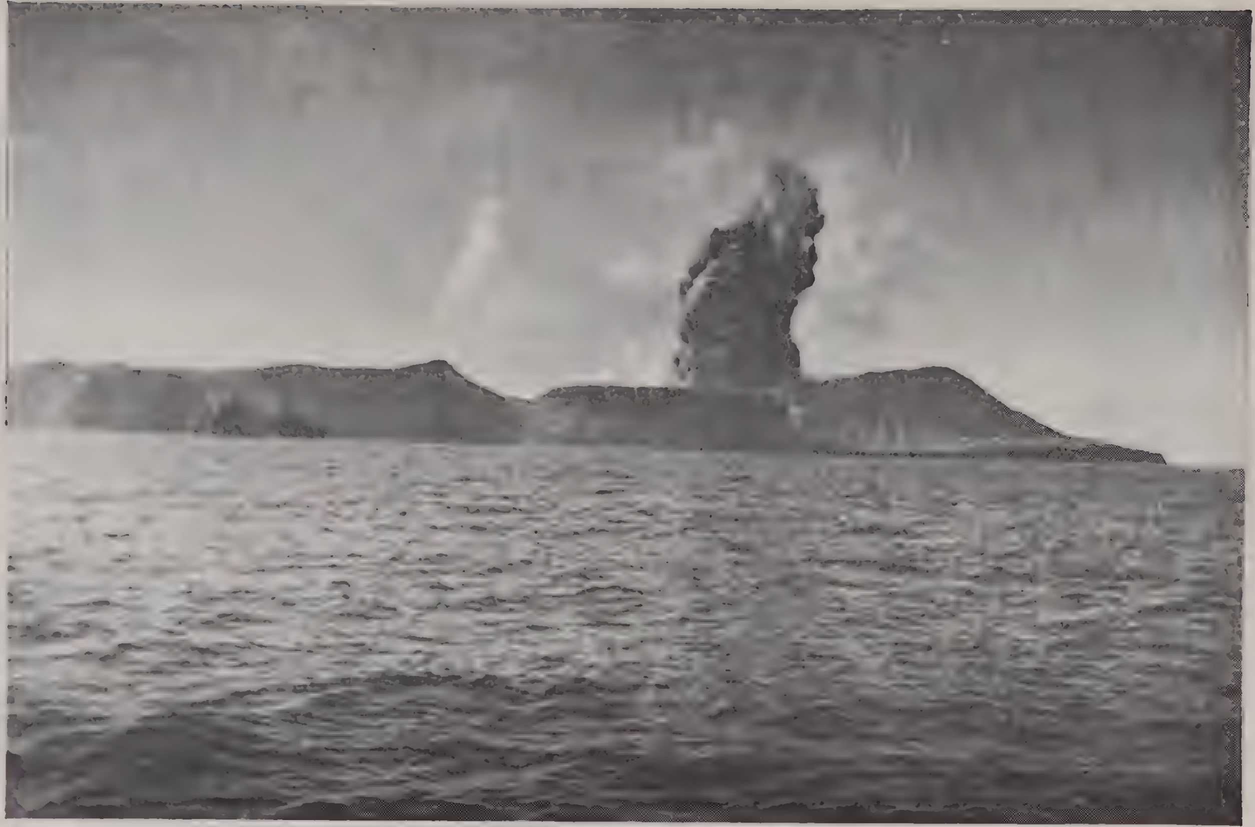

PLATE III

PLATE IV

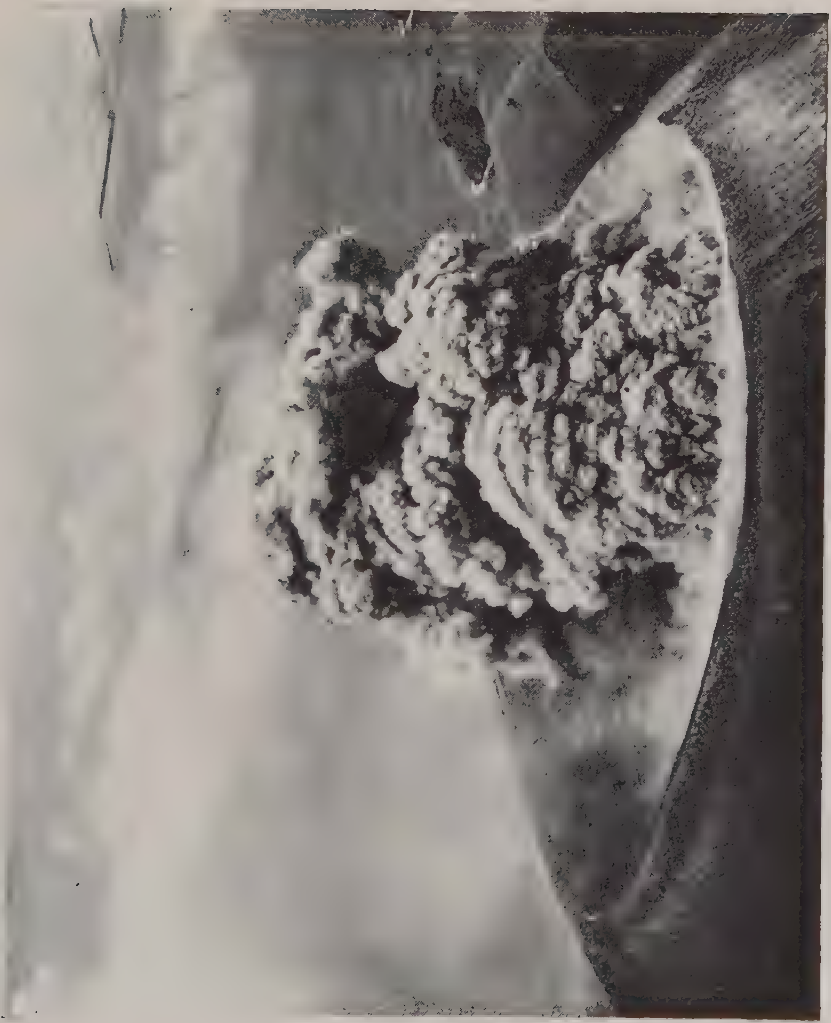

PLATE V

PLATE VI

PLATE VII

PLATE VIII

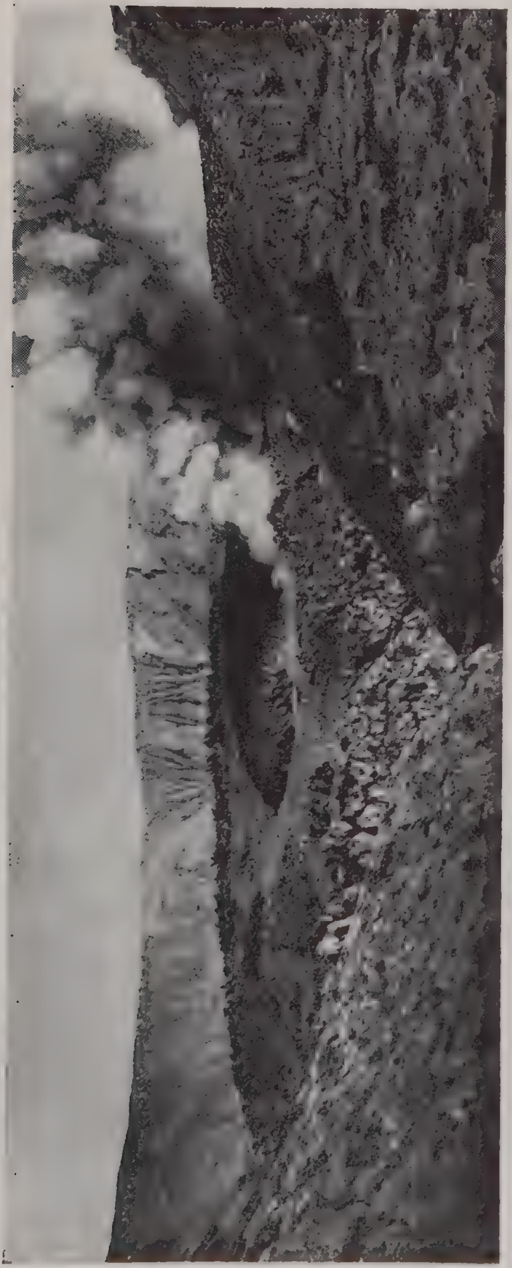

PLATE IX

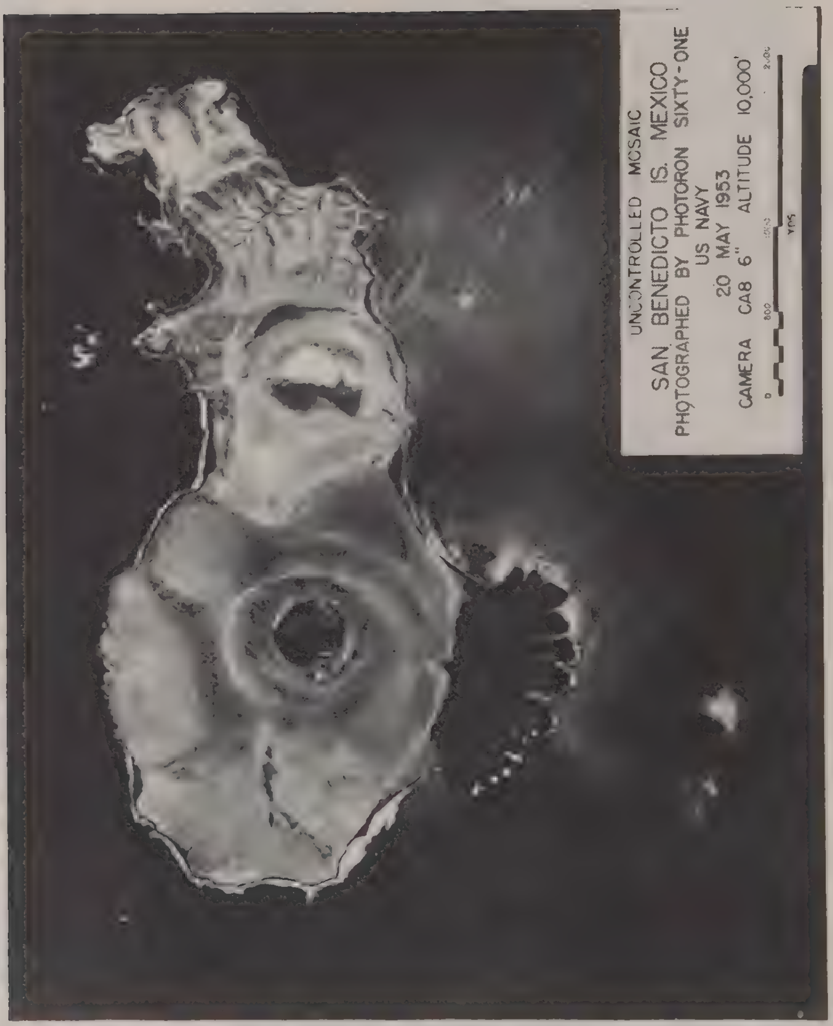
UNCONTROLLED MOSAIC
SAN BENEDICTO IS. MEXICO
PHOTOGRAPHED BY PHOTORON SIXTY-ONE
US NAVY
20 MAY 1953
CAMERA CA8 6" ALTITUDE 10,000'
0
500
1000
2000
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PLATE X

Nuclear Science and Oceanography

By R. Revelle, T. R. Folsom, E. D. Goldberg, and J. D. Isaacs,* USA

Our earth is unique among the planets in its possession of a world-encircling ocean. This watery cloak is intimately related to such diverse phenomena as petroleum, climates and life. Major obstacles to understanding of these phenomena arise from the magnitude and subtlety of oceanic processes.

Many scientific problems of the ocean can be resolved into questions concerning the fluxes within its realms. Promising possibilities exist for study of these fluxes by the tracer techniques of nuclear science, but to date the possibilities have been only timidly explored. A more vigorous and imaginative application of nuclear tools in the marine sciences would certainly result in important breakthroughs.

The practical problem of oceanic disposal of nuclear wastes involves nearly all phases of oceanography. Conversely the use of radioactive materials as tools in oceanography must lead to a better understanding of the disposal problem.

NATURAL RADIOACTIVITY IN THE OCEAN

In considering possible applications of radioactivity to the study of the ocean, two facts are of prime importance: the very low level of natural radioactivity in the sea and the enormous volume of the ocean waters. Both of these facts are well illustrated in Table I.

The amount of radiopotassium per unit volume of average igneous rocks is about 100 times the amount in the ocean. Uranium in the rocks is about 3000 times as great as in an equal volume of sea water, radium about 10,000 times, and thorium a million times. On the other hand, the carbon-14 per unit volume of sea water is 300 times that in air and the total carbon-14 in the ocean is between 50 and 100 times the total in the atmosphere. Nearly all tritium is in the ocean, chiefly in the top 50 to 100 meters.[2]

Potassium-40, with a gamma-radiation energy of 1.5 Mev, is the principal radioactive nuclide in sea water. It yields about 100 times as many disintegrations per unit volume and time as the uranium and thorium series and 50 times as many as rubidium-87. The very low thorium-uranium ratio in sea water indicates that the effective "solubility" of thorium is far less than that of uranium. We would expect that the thorium isotope, ionium, one of the intermediate products in the uranium-radium series, would also have a very low concentration, and that for this reason the amount of radium would be much lower than the equilibrium value computed from the uranium content. Table I shows that this is in fact the case. Both uranium and thorium are effectively "saturated" in the ocean and the rate of precipitation in the bottom sediments is very nearly equal to the rates at which these elements are brought to the sea by rivers.

In contrast to the low level of activity per unit volume, the total amounts of radioactive nuclides in the ocean are very large, ranging from 460,000 megacuries for potassium to 8 megacuries for thorium. Fission of all the uranium-238 and -235 in the ocean would yield 2×10^{33} ergs of energy, equal to 30 times the total amount of solar energy falling on the earth's surface each year, or 1.2×10^{6} times the present annual consumption of energy by human beings and their industrial civilization (about 4.5×10^{10} megawatt hours).[30]

USE OF ISOTOPIC TRACERS IN THE MARINE SCIENCES

Currents and Diffusion

Among the basic questions of the marine sciences are: where, and how fast and by what mechanism do the ocean waters move? We are interested in the well-defined transport of ocean currents and in the apparently random motion called diffusion. These two processes are related by the following equation, in vector notation:

$$\frac{\partial c}{\partial t} = \nabla \cdot A \nabla c + Q - v \cdot \nabla c \qquad (1)$$

where c is the amount per unit volume of something present in the water, $\partial c/\partial t$ the time rate of change of concentration at a fixed point, v the vector current velocity, A the effective diffusion coefficient, and Q a source function. For radioactive substances that are unaffected by biological activity, $Q = \lambda c$, where λ is the radioactive decay constant.

We may conveniently think of the ocean outside the Arctic and Antarctic as a two-layer system, consisting of (1) an upper layer, ten to several hundred meters thick, in which the temperature is constant with depth during winter months, vertical diffusion is rapid, and currents vary markedly in speed and direction over short periods of time, and (2) a lower layer, several thousand meters thick, in which temperature decreases with depth nearly all the way to the bottom. This layer is stably stratified, that is the density of the water increases and the entropy decreases with depth, and vertical turbulence appears

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* Contribution (New Series, No. 794) from the Scripps Institution of Oceanography, University of California, La Jolla, California.

Table I. Radioactivity of Sea Water

Nuclide	*Concentration (gm/cm³)*	*Specific activity (number of disintegrations/cm³/sec)*	*Total amount in ocean (megatons)*	*Total activity in ocean (megacuries)*	*Energy of γ-radiation (Mev)*
K^{40}	4.5×10^{-8}	1.2×10^{-2}	63,000	460,000	1.5‡
Rb^{87}	8.4×10^{-8}	2.2×10^{-4}	118,000	8400	no γ
U^{238}	2.0×10^{-9}	1×10^{-4}*	2800	3800	.05 – .82
U^{235}	1.5×10^{-11}	3×10^{-6}*	21	110	.06 – .18
Th^{232}	10^{-11}	2×10^{-7}*	14	8	.03 – .08
Ra^{226}	3.0×10^{-16}	3×10^{-5}*	4.2×10^{-4}	1100	.18 – .60
C^{14}	4×10^{-17}	7×10^{-6}	5.6×10^{-5}	270	no γ
H^{3}†	8×10^{-20}	2.5×10^{-5}	1.5×10^{-9}	12	no γ

*Activity of nuclide + daughter products. †Only in top 50–100 meters of the ocean. ‡ $\gamma/\beta = 0.1$

to be virtually non-existent. The lower layer seems to behave as if it consisted of a series of separate sheets, of great horizontal extent and extreme thinness, piled up and moving quasi-independently.

In the open ocean, current speeds in the upper layer vary from a few centimeters to one or two hundred centimeters per second. The currents in the lower layer are presumably smaller but little is known about them.

Up to the present, radioactive tracer techniques have not been much used to study the currents in the upper layer, although their application has been encouraged by the pioneer studies of Miyake and coworkers.[1] Nevertheless, they have furnished important information about the diffusion. Von Buttlar and Libby[2] measured the amounts of tritium present in rivers, ocean surface waters, and in rain. Assuming that storage occurs on land and in the ocean but not in the atmosphere, their results can be expressed approximately in the form

$$\lambda ch = P = R_s\,(T_s - 0.25) \qquad (2)$$

where R_s is the average rainfall over the sea in cm/sec, T_s is the average tritium content of this rain in atoms/cm³, P is the rate of tritium production by cosmic rays, in atoms/cm² sec, and c is the tritium content of sea water in atoms/cm³, assumed uniform from the surface to a depth h. Von Buttlar and Libby found a best value for P of 0.14 .Taking c as about 1.7×10^4, the weighted average of their measured values for surface sea water, and λ as 1.7×10^9 sec^{-1}, h becomes 50 meters. This is very roughly the average depth of the upper layer in the sea. We must conclude that over times of the order of 12 years, the half-life of tritium, there is little interchange between the upper layer and the waters at greater depth.

One of us (Folsom) has investigated the vertical mixing in the upper layer with the aid of artificially radioactive substances (fission products). These were introduced at the surface in an area where the upper layer was about 100 meters thick. The rate of downward motion of the lower boundary of the radioactive water was approximately 10^{-1} cm/sec^{-1}. This motion ceased abruptly at the bottom of the upper layer.

Horizontal diffusion in the relatively shallow waters of Bikini lagoon was studied by Munk, Ewing and Revelle[3] using the observed spreading of radioactive material (fission products) introduced more or less uniformly through a column of water 60-meters deep. The average value of the horizontal component of the effective diffusion coefficient, A_h, during three days in which the radius, r, of the radioactive area increased to about 4 kilometers, was found to be 1.5×10^5 cm²/sec^{-1}, and $A_{h/r}$ was close to 0.5 cm/sec^{-1}. This value of $A_{h/r}$ is in good agreement with estimated values of this ratio, obtained by other means elsewhere in the ocean, over a range from 10^3 to 10^8 cm in r.

The stably stratified waters below the upper layer are believed to move in a series of great current systems superimposed on one another. Little is known about any of these systems but it is generally assumed that currents in the deep and bottom waters have a significant meridional component (north-south or south-north). These waters sink from the surface in the Arctic and Antarctic, where vertical density stratification is minimal or lacking. They move slowly to lower latitudes under the overlying less dense waters, then slowly return to very high latitudes where they are again mixed with surface waters. At the surface, they come into at least partial equilibrium with the carbon dioxide in the atmosphere, and hence with the atmospheric carbon-14. After the waters have sunk they retain the carbon dioxide acquired at the surface, but the carbon-14 slowly decays. Because of the density stratification, vertical diffusion can be neglected, and if we also neglect horizontal diffusion, and assume that a steady state exists, Equation 1 is reduced to:

$$v \cdot \nabla c = \lambda c \qquad (3)$$

Analysis of carbon-14 in deep-water samples should therefore tell us something about the average meridional component of velocity from the source in high latitudes to the point at which the sample was collected. Kulp[4] has attempted measurements of this type. The preliminary results are complex but not inconsistent with a meridional velocity between 1 and 0.01 cm/sec. Estimates of this velocity component by other methods give values of the order of 0.1 cm/sec, that is, a round-trip time of several hundred years for the deep waters, from high latitudes to the tropics and back again.

(740)

The authors have recently studied the processes occurring when sea water containing mixed fission products is introduced into the lower layer. The radioactive water was observed to spread laterally in a sheet, with a thickness of the order of a meter and an area of 100 or more square kilometers, at a depth determined by the vertical density distribution, that is the radioactive water spread outward along an iso-density surface. The center of the sheet moved horizontally with about the same velocity as the waters just above and below it. Vertical mixing, at least in the upper part of the lower layer, evidently is very slow.

The extreme vertical stability of the lower layer gives promise of the use of relatively small amounts of radioactive substances as a tool for studying the horizontal diffusion and the horizontal and vertical components of the currents at depth. Because the water behaves as if it consisted of thin, independent sheets, we are concerned chiefly with the two-dimensional spreading of radioactive material. We need to follow the radioactive water from shipboard, and experience shows that to do this successfully we must be able to detect the introduced radioactivity by lowering a measuring instrument into the water from the ship.

To obtain some insight into the possibilities of such experiments, let us suppose that N curies of a gamma-radiating nuclide are introduced in solution at a point in the lower layer and the solution spreads vertically through a depth h*cm*. Over what area can it spread horizontally and still be detected by *in situ* measurements with a probe immersed in the radioactive water? Let r be the radius of the area over which the radioactive material can spread and yet be detected. The cosmic ray background may be virtually neglected below a few tens of meters. Let t be the counting time, V the equivalent volume of the detector, e the counting efficiency, B the specific gamma activity of natural sea water in photons/cm^3/sec^1, and n the fractional error in measurement of introduced radioactivity. For 95% probability that a measured value gives the concentration of the introduced radioactivity with an error less than n, we have, if we neglect the decay of the radioactive material:

$$\pi r^2 = \frac{3.7 \times 10^{10}\, NVten^2}{2h\,[1 + (1 + 2n^2\,BVte)^{1/2}]} \tag{4}$$

This equation rests on the well-known fact that counting errors are inversely proportional to the square root of the number of counts. If the background is continuously measured, the time limitation does not apply to background measurement. The denominator of Equation 4 becomes $2h\,[1 + (1 + 2\,n^2\,BVte)^{1/2}]$. This increases r (max) roughly by 1.2.

If possible, the error in measurement of the introduced radioactivity should not exceed 50%, that is $n \leq 5$. For measurements *in situ*, the counting time is limited by the difficulty of maintaining an instrument suspended at a fixed depth in the sea from a rolling and drifting ship. Other practical considerations limit the speed with which the probe can be raised or lowered to not less than 10 cm-sec^{-1}. The largest practical value of h/t is therefore 10, and, if possible, t should not exceed 5 sec.

With the instruments described below, $e = .03$ and V about 10^3 cm^3. From Table I, $B = 1.2 \times 10^{-2}$ photons/cm^3-sec^{-1}. A "reasonable" value for N is 10 curies. Our experience suggests that h will not exceed 100 em within the duration of the experiment.

With $t = 5$ and the other stated numerical values, $\pi_r{}^2 \leq 2.9 \times 10^{10}$ cm^2, and r (max) is slightly less than 1 km. The instrument will record only 19 counts during the counting interval. Of these, 0.2 counts will be from the oceanic background. Unless great care is exercised, the internal background of the instrument will be a serious limiting factor.

The situation can be improved by use of a scintillation-type detector with e about .25. For this value of e and $t = 10$, the maximum detection area becomes 23 km^2 and $r = 2.7$ km. For $n = 1$, that is for a 95% probability of detecting the radioactivity but without a reliable measure of its concentration, the maximum detection area is 52 km^2 and r is 4.1 km.

If we employ one of the nuclides listed below (Table II) such as rubidium-86 with a gamma energy of 1.1 Mev, and the instrument is capable of discriminating against the 1.5 Mev radiation from potassium-40, the permissible dilution can be increased. Gates and Eisenhauer[5] have computed the energy spectrum of the scattered radiation from single frequency sources. They show that for a source energy of 1.5 Mev the proportion of energy in a 0.2 Mev band around 1.1 Mev is about 10%, whereas for a 1.1 Mev source 50% of the energy will be in this band. With proper counting conditions it should be possible to triple or quadruple the detection area.

Thus far we have not considered the decay of the introduced radioactive material. Because of the linear relation between A_h and r, the duration of the experiment will vary almost directly with the radius of the detection area. For the computed values of r, the observation time probably cannot exceed a week, so that with nuclides of suitable half-life the decay will not be very significant.

We have given some thought to a single nuclide that might be used for experiments of the type described above. The prerequisites for such a tracer include a half-life compatible with the time constant of the vertical and horizontal motion of the water and the diffusion, and yet not so long as to engender potential hazards to health through contamination of marine products of commerce or beaches. Further, the half-life must be such that delivery from the production site to the point of the experiment can be made without excessive decay. Such considerations indicate that the half-life should be of the order of a week to a month. The tracer should form a readily soluble ionic species in sea water, so that the volume of material handled can be minimal and precipitation and settling out of colloidal particles from the radioactive layer will not occur. Elements of groups IA,

Table II

Isotope	*Half-life*	*Cost per curie*	*Specific activity available*	*Gamma energy Mev*
Rb^{86}	19.5 day	$1000.	9 mc/gram	1.1
I^{131}	8.0 day	750.	Carrier-free	0.36 and 0.72
Ba^{140}	12.8 day	500.	Carrier-free	0.16 and 0.54

IIA, VA, VIA and VIIA in the periodic table are preferable. The tracer should be cheap and readily available in multi-curie amounts. Consequently it should either be produced in a pile by neutron-gamma reactions or be a fission product that is readily separable. High specific activities are desirable. The tracer should be a gamma-ray emitter with energy between .2 Mev and 1.3 Mev so that *in situ* assays can be made readily and discrimination of the isotope from naturally occurring nuclides can be accomplished. Three promising isotopes are listed in Table II. Rubidium and iodine decay to stable daughters, while barium is parent to gamma-ray emitting La^{140}, which increases the total activity after a few days.

Composition of Sea Water and Marine Organisms

The concentration of minor elements in sea water is not accurately known, in fact many elements are present in such small amounts that they are undetectable by older analytical methods.

Assay of trace elements in the concentration range of parts per billion or less has been advanced by two new analytical techniques, activation analysis and isotope dilution. Cesium, arsenic and rubidium in marine waters were determined by the former method by Smales and his co-workers[6,7] using the Harwell pile. An imaginative extension of this technique was employed by Stewart and Bentley,[8] who measured the uranium content of Pacific Ocean waters by counting the fission-fragments from uranium in sea salt irradiated in the Argonne heavy-water reactor CP-3. The isotopic dilution technique was applied by Rona and co-workers[9] to obtain the uranium content of Gulf of Mexico and North Atlantic waters. Such new developments as pile activation of samples followed by gamma-ray spectroscopy should further advance our knowledge of the chemical composition of the ocean.

Many elements known to be present in trace amounts in sea water and some, such as thallium, cadmium and zirconium, which no one has been able to detect, exist in high concentrations in marine organisms. What are the paths by which these trace metals are concentrated in living creatures?

Two general processes for the transfer are evident. The first involves direct uptake of dissolved substances. For example, vanadium exists in the oceans to the extent of 1 microgram per liter, while the blood of certain ascidians (sea squirts) can contain up to 10% vanadium, a concentration of a hundred million. By the use of cyclotron-prepared radiovanadium, Goldberg, McBlair and Taylor[10] were able to show that these animals can assimilate ionic vanadium from sea water and that the reactive site for the vanadium uptake is the mucus. Such accumulation parallels the uptake of iodine by the thyroid, and its specificity equals that of the best analytical reagents devised by man.

The mucus of marine pelecypods has been shown to be the adsorbing agent for strontium-90 by Fretter[11] and for calcium-45 by Rao and Goldberg.[12] Spooner[13] treated species of algae with carrier-free radioactive strontium and yttrium. Brown seaweeds extracted strontium upon their surfaces by factors of 10 to 40 over sea water, while red algae took virtually all the ionic yttrium from the water.

A preliminary survey[14] indicates not only that trace metals in marine organisms are retained by fairly strong chemical bonds but also that the relative degree of concentration of ions follows the order of the relative stability of these ions in organic complexes as given by Schubert.[15] Fission products consist dominantly of elements that form such relatively strong chemical bonds with organic compounds. The Noddacks[16] found for elements within the fission product spectrum the following enrichment factors for wet weight of marine animals compared to sea water: Mo, 600; Ag, 2000; Zn, 3250; Cd, 450; Ge, > 760; Sn, 270; As, 330; and Sb, > 30. Black and Mitchell[17] found the following concentration factors for algae: Zn, 400–1400; Mo. 2–15; Sr, 8–90. In preliminary analyses we have found that organisms living in waters containing mixed fission products concentrate the radioactivity by a factor of approximately 1000.

Further understanding of the intimate chemistry of these powerful concentration processes would be important not only to biologists interested in metabolism, but also to inorganic chemists seeking specific reagents for analytical methods. Knowledge of the functional groups within mucus and plant slimes may best be obtained by already familiar tracer techniques.

Marine organisms also accumulate trace elements by the assimilation of particulate matter. Iron, a necessary nutrient for plants, exists in the ocean principally in colloidal form. Goldberg,[18] utilizing radioactive iron, demonstrated that growing marine diatoms (microscopic plants) assimilate particles of hydrated iron oxide, but do not recognize ionic iron in complex form such as citrate, ascorbate or humate. Zirconium, titanium and other anions are scavenged from sea water by particles of hydrated oxides of iron and may be incorporated into plants with the iron. Such reactions could explain the high amounts of titanium and zirconium reported in "red tide" waters near the west coast of Florida in October and November, 1952, by Collier.[19]

Organic Productivity

Organic productivity in the ocean is among the major problems of marine biology. Fundamental to this problem is the determination of the amount of organic matter photosynthesized from inorganic substances by the marine autotrophic plants, the basis of life in the sea. Nielsen[20] developed a powerful and elegant technique for this determination, using carbon-14. He was concerned primarily with the microscopic plants that make up the plant plankton of the open sea. In Nielsen's method, tracer amounts of radiocarbon in the form of bicarbonate are added to a sample of water and plant plankton, freshly collected from a point in the sea. The sample of sea water and plants is placed in a transparent glass bottle and lowered to the depth in the ocean from which it was taken, or placed in a water bath illuminated to the light intensity at that depth. After a measured time interval, the water and the contained plants are separated by filtration. The radioactivity of the filtered organisms gives a direct measure of the amount of carbon assimilated in photosynthesis.

From measurements of this type in many parts of the ocean, Nielsen[21] estimated that the average net photosynthetic production is about 1.5×10^{-10} gms/-cm^2/sec or a total net production for the whole ocean of about 1.5×10^{10} tons of carbon per year. This total production is about the same as that estimated for the lands of the earth. In this study Nielsen mapped such marine deserts as the Sargasso Sea, where his measured productivity was less than $.5 \times 10^{-10}$ gm carbon/cm^2/sec, and such oceanic "Edens" as the waters of the Benguela current on the west coast of Africa, where he found apparent rates of production of 25×10^{-10} gm carbon/cm^2/sec. Other workers, notably Riley,[22] using quite different techniques, have arrived at total productivity estimates for the ocean that are an order of magnitude higher than Nielsen's. The discrepancy is not resolved.

Beaches and Sedimentation

The sedimentary cycle, in which continental rocks are eroded and their components transferred via the ocean to sedimentary deposits, can be considered as a set of fluxes. Radioactive substances are naturally present or can be incorporated in these fluxes and can be used as tags.

In Santa Barbara, California, there is a destructive longshore transport of beach sand, estimated by Johnson[23] to be approximately 770 cubic yards per day. To prevent beach erosion, the path of the sand must be ascertained before remedial measures can be taken. Tracer sand grains for this purpose must be easily and rapidly distinguishable from the mass under study. Further, the size distribution, density and shape of the grains must be close as possible to those of major components of the sand. In the past, various nonradioactive tracers have been employed for problems of this type, but these have suffered from a number of inadequacies. The densities and other properties of colored glasses or rare minerals are usually so unlike the sand under study that they give erroneous pictures of the transport. Dyed or etched components of the sand itself are difficult to distinguish from the untreated grains, and the treatment is usually ephemeral.

In an attempt to obtain a more suitable tracer, Goldberg and Inman[24] irradiated quartz grains in the Oak Ridge National Laboratory slow-neutron pile. They found that the only significant induced activity is that of phosphorus-32. This nuclide is a pure beta emitter with a half-life of two weeks. By incorporating the activated quartz in natural sands, and by using radioautographic techniques, one active grain in one million inert grains is readily distinguished. In such an area as Santa Barbara, it should be possible to trace the sand transport over a 30-day period to dilutions of one in a million using 13 millicuries of irradiated material. This amount, after dispersal over the beach area, would certainly not create a health hazard. Quartz samples from various parts of the world show adequate phosphorus contents for the technique. Quartz is usually one of the principal components of sand and can be separated easily in a pure state by heavy-liquid, magnetic or electrostatic methods.

Natural radioactive substances have been used to determine the rates of accumulation of deep sea sediments. In these sediments, the radium content is commonly much higher than the equilibrium value for the uranium. As shown by Holland and Kulp,[25] the sedimentary particles probably extract from the sea water, by processes of base exchange and adsorption, both radium itself and its precursor, the thorium isotope, ionium. Ionium has a half-life of 8.3×10^4 years, while deep sea sediments accumulate at rates of the order of 1 cm/1000 years. The radium in equilibrium with the ionium ought therefore to decrease to about half the surface value at a depth in the sediments of the order of one meter.

In its simplest form the method of determining the rate of sedimentation depends on the assumption that migration of the radioactive elements does not take place after the sediments are deposited. Indications that migration does in fact occur were obtained by Arrhenius and Goldberg.[26] In studies of the radioactivity of cores of deep sea sediments from the Pacific Ocean, they found that sedimentary layers with a high concentration of radium also contain an abundance of the zeolite, phillipsite. This mineral forms within the sediment and as it forms, radium must be accumulated within it from the interstitial water. Apparently the resulting concentration gradients of radium in the interstitial water bring about a migration to the phillipsite-rich layer.

Interactions between the Ocean, the Atmosphere, and the Lithosphere

The ocean acts as an aqueous reservoir for many of the components of the atmosphere. New techniques, using stable and unstable isotopes, are becoming increasingly useful in studying the interactions between the two great earth fluids. We shall select one example.

The interchange of carbon dioxide between the atmosphere and the ocean was recently elucidated by Suess.[27] He studied the carbon-14 content of tree rings, in an attempt to ascertain whether the carbon dioxide in the atmosphere has been increased by the combustion of the fossil fuels. The specific activity of carbon-14, corrected for decay, is apparently a few per cent less in tree rings grown in the present time than in the 19th Century. This dilution of the cosmic-ray produced activity coupled with the well-known quantities of combusted fuels leads to an average lifetime for the CO_2 molecules in the atmosphere and terrestrial biosphere of 20 to 50 years before solution takes place in the ocean.

The origin, evolution and geologic history of the ocean are fundamental problems in the earth sciences and biology. It is apparent from differences in abundance of the rare gases in the earth and the stars, that our ocean, as well as our atmosphere, evolved during a secondary stage of earth evolution. The elements in the present day ocean were not initially retained as an atmospheric blanket but were held chemically within the earth's interior. On the other hand, the amounts of these elements now present on the earth's surface far exceed the amounts that could have been produced by weathering of igneous rocks. When and how did these materials seep out of the earth?

Perhaps the processes giving rise to the ocean and the atmosphere are recorded in the isotopic composition of the interacting phases. Craig[28] has begun to investigate the variations in the ratio of C^{12} to C^{13} in all types of natural material, in an attempt to determine this ratio in primordial carbon and the rate of outflow of carbon from the earth's interior. This attempt, if successful, might tell us how the compositions of the ocean and the atmosphere have varied throughout geologic time.

Thode and his co-workers[29] studied S^{32}/S^{34} ratios in a variety of marine sulphate and sulphide deposits. In reactions involving sulphate-sulphide equilibria, the sulphates become enriched in the heavier isotope. Biological processes provide the mechanism for the oxidations and reductions undergone by the sulphur isotopes. The first significant indications of isotope fractionation are found in pyrites and limestone sulphates formed circa 700–800 million years ago. Thode concludes that marine autotrophic organisms may have arisen during this era.

INSTRUMENTS FOR SURVEY OF RADIOACTIVITY AT SEA

The present Scripps Institution equipment for surveying ocean radioactivity was designed primarily for economy and reliability under severe shipboard usage; nevertheless, it has considerable flexibility in range and sensitivity and is readily adaptable to several types of ocean measurements—above water—on the sea-surface—and under the surface to depths of about 1000 meters. The detector is designed to withstand hydrostatic pressures at 2000 meters and hence underwater measurements are limited to determination of fairly hard gamma constituents—those capable of penetrating the steel shell of the detector. This limitation is not a severe one.

Requirements peculiar to shipboard use led to the choice of halogen-filled Geiger counters. In one class of instruments, ten or more slender Geiger tubes of a type (Anton #315) designed for oil-well exploration are combined in parallel so as to feed their pulses to a simple pulse-shaper and amplifier. The detector reports activities corresponding to local gamma intensities from 100 mr/hr down to the cosmic ray background in air. This range is divided into six minor ranges by modifying the pulse-amplifier gain.

For measurements of higher activities, the conventional Geiger tubes are replaced by a group of ten or more gas discharge tubes of the "integrator" type which (1) are undamaged by high fluxes, (2) report by means of currents so high that no amplifier is needed and (3) compress their signal report of a very long range of gamma intensities into a single logarithmic response signal (four to five decades).

Either of the two discharge tube arrays can be used interchangeably in several tubular protective shells. These shells also contain batteries, cable terminals, and range selector sensitivities. They are roughly two meters long, with an outside diameter of 8 cm. The cylindrical walls are about 7-mm thick; both ends are fitted with removable plugs sealed with "0" rings. One end-plug joins a cable which brings the signal to an electrical recorder on deck.

For vertical sounding, the cylindrical detector assembly is attached to a multiconductor cable, about 1000 meters long and 7 mm in outside diameter, protected externally by two layers of steel wire armour. This cable is wound in and out on a small winch which is driven by an oil transmission system, in order to escape induced signals. The winch is provided with amalgam slip-rings permitting continuous electrical connection of the detector through four conductors to the recording devices on deck. We have called this combination a radiological sonde or probe. It permits rapid survey of water to the depth of the cable (Fig. 1a). It may also be towed aft of a ship steaming at full speed, and then records the horizontal profile of activity in the near-surface water.

The radiological sonde contains a pressure indicator (a bourdon-actuated potentiometer) so that a signal reporting the depth is sent up one of the conducting wires. This permits the radioactivity to be measured as a function of depth independent of the ship's speed, the amount of cable out, or the state of the sea and weather.

The assembly also carries a resistance-bridge temperature indicator which reports on a separate conductor to the deck.

The cable terminates in the ship's laboratory in a pair of recorders, each of which plots with a pen on chart paper the depth signal on the vertical coordinate (Y axis). One recorder plots the radiation signal on its X axis; the other plots the temperature signal. Consequently as the probe is lowered or

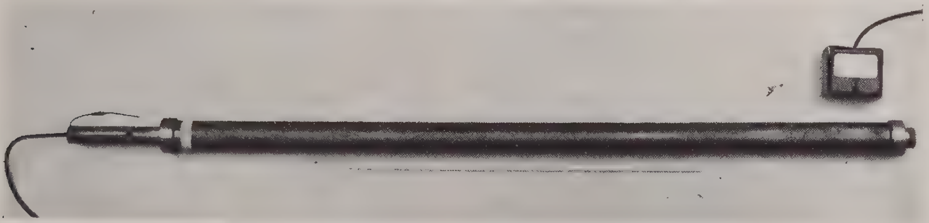

Figure 1. (A) A sonde rigged for hand lowering. For winch lowering, a three conductor armored cable is used rather than this rubber covered cable. The special winch permits deck recording of radioactivity vs depth and temperature vs depth;

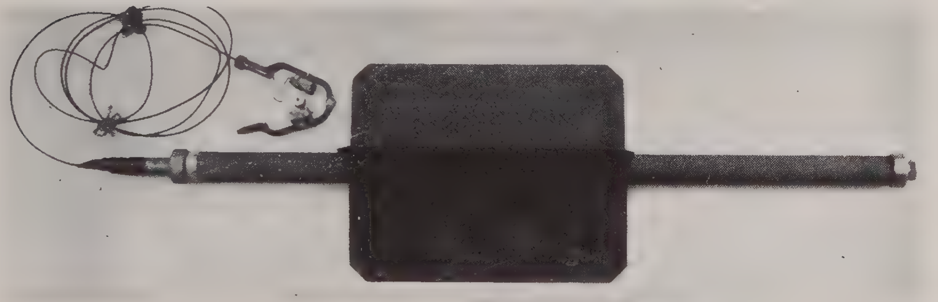

Figure 1. (B) A sonde rigged for horizontal towing. The signal is conducted through the armored pennant (on the left) through the special swivel and perforating clamp, and into the plastic coated towing cable. This arrangement permits fast towing of sondes at five or more different levels, transmitting to a single deck recorder

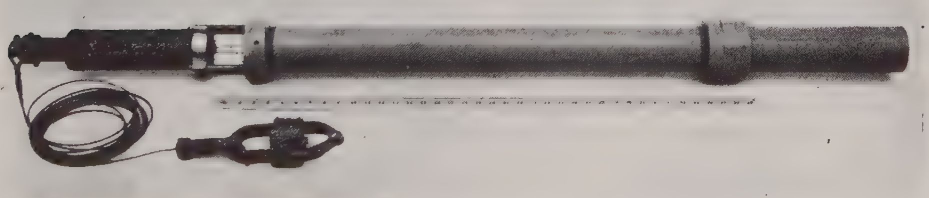

Figure 2. (A) A sampler rigged for towing. This can be set to collect a sample when a predetermined level of activity is encountered. It is towed from a depressed cable by the swivel clamp, which is rigged here for towing but not signalling;

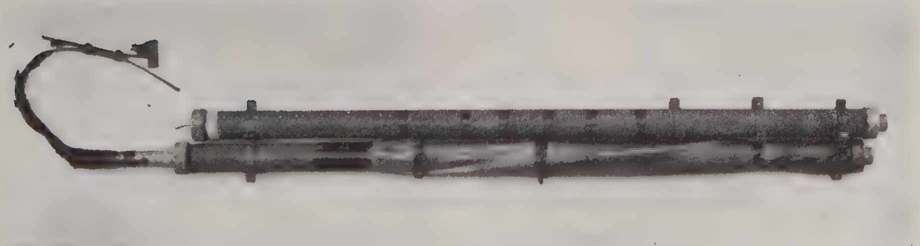

Figure 2. (B) The sonde rigged for winch lowering with self-actuating sampler attached. Interchangeable components permit versatility and improvisation in the field (as in the above) to attack special measurement problems

raised, radiation and temperature are plotted directly against depth. Range, sensitivity, and response rate of the pressure and temperature devices can be modified widely by varying the circuit parameters, but none of the precision traditional in physical oceanography has yet been attempted. The temperature and pressure plots serve mainly to round out the graphical picture of the radioactivity in the water, and to aid in rapidly locating a radioactive layer.

When provided with a set of fins, the cylindrical detector assemblies can be towed in groups of two or more behind the ship, attached (by means of special swivel clamps and short pennants) to a heavy cable kept submerged by a mechanical depressor (Fig. 1b). In this use the temperature element is replaced by a simple electronic integrator circuit which converts the Geiger tube signal into time-spaced signal "pips." These low voltage, time-spaced pips can be transmitted up an ordinary heavy towing cable to a suitable deck recorder, provided the towing cable has been covered with a thin polyvinyl or nylon coating.

This depressed-towing technique is useful when continuous measurements are desired at two or more depths down to about 400 meters. Such depths can be obtained at towing speeds of 7 to 10 knots (Fig. 5).

The vertical sonde assembly may be used as an indicator of gamma radiation coming through the air from the sea surface, provided it is mounted in an exposed position where the radiation can strike it. Our practice has been to mount the unit on the side of the ship about one meter above the sea surface, and to record its signal continuously against time with a suitable electronic recorder.

Beside this running log of surface activity, a directional indicator of gamma radiation from the sea surface is useful in detecting boundaries of active sea water. This consists of a pair of sensitive Geiger tube arrays (each having 10 tubes in parallel) mounted side by side on an elevator part of the ship near the bow. Four inches of lead are placed between the two sensing arrays so as to divide the sea surface "viewed" by the detectors into two halves. One detector sees only the rays coming from port, the other only those from starboard. Each detector has its own radiation indicator (in the form of a simple microammeter) and the two indicating meters are mounted side by side in front of the helmsman on the ship's bridge. The officer on watch obtains not only an indication of the presence of radioactive surface water but also immediate information as to which way to steer to reach it.

Ordinary water samplers may be attached to the electrical cable of the vertical sonde. However, in attempting to sample the radioactive layers at depth, it has been found difficult to trip the sampler by the usual messenger technique. The messenger moves too slowly, and the rolling of the ship jerks the probe in and out of the thin active layer. We have tripped the samplers automatically, using the radiation signal from the probe (Fig. 2).

THE DISPOSAL PROBLEM

Some of the information and many of the techniques described in preceding pages can be applied to the problem of disposal of atomic wastes in the sea.

The rate of consumption of energy by human beings and their industrial civilization is doubling about once every 30 years. Let us assume a future energy utilization of about 2.5 times the present one, estimated by the Woytinskys[30] as 4.5×10^{10} megawatt hours. If all this energy were obtained from nuclear fission, and if the radioactive wastes were dumped into the ocean after a month's storage, the total radio-

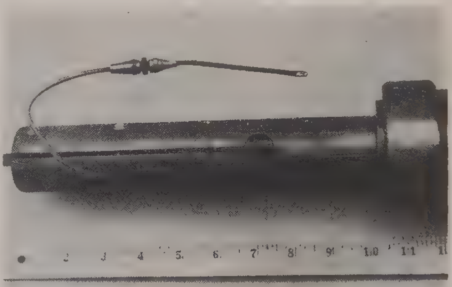

Figure 3. Cable termination of a sonde. The small tube is the pressure transmitter pickup

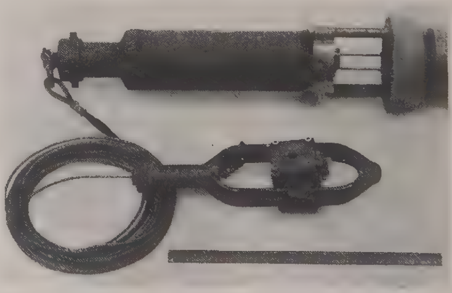

Figure 4. Termination of a sampler showing the actuator, towing pennant and swivel for attachment to the towing cable

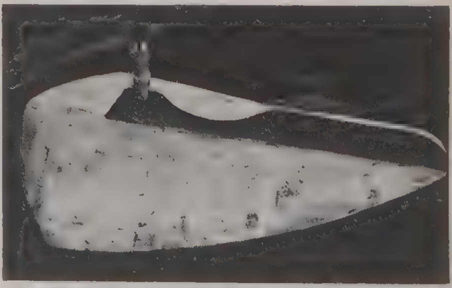

Figure 5. Aluminum depressor for the towing cable. The special insulating swivel isolates the depressor from the cable circuit

activity of the ocean would be increased by 3.7×10^6 megacuries, approximately eightfold. The total mass of fission products added per year would be 5000 tons.

The average radioactivity of sea water would still be quite low, but because of the very slow mixing, some water masses might show a thousandfold increase. For example, radioactive wastes introduced into the upper layer might remain there for many years, and would be diluted by a volume of water only a fiftieth to a hundredth the volume of the ocean. We can speak with much less certainty about the lower layer. Waste products in solution, introduced at a particular location and depth in the lower layer, might spread out over a very wide area in a thin, nearly horizontal sheet of concentrated activity. But rate of spreading and current transport of such a sheet are hard to estimate with present data.

A tenfold increase in the radioactivity of a particular water mass, if brought about by the presence of fission products, would probably result in an increase of several orders of magnitude in the radioactive content of the organisms living in the water. This would be expected because of the tendency of marine plants and animals to concentrate nuclear species having an intermediate position in the atomic table. Average activities of 100 disintegrations/sec[1] per gram of wet organic matter would be likely.

Some elements would be much more concentrated by organisms than others, and there would be significant differences between different groups of organisms and between parts of the same organism. Wastes introduced in solid inorganic phases might be concentrated by filter-feeding animals, such as shrimps and certain mollusks. Zinc would be especially concentrated in the spleen, liver, and stomach of fishes, the average enrichment factor on a wet weight basis being 10^4, according to Vinogradov.[31] It is of interest to note that the isotope Zn^{65}, presumably arising from nuclear detonations, has been found concentrated in the internal organs of fish by Japanese investigators.[32] The possibility of human ingestion of radiozinc from fission products is reduced by the fact that the zinc-rich organs normally are not eaten.

The hazards to human beings from marine disposal of radioactive wastes might well be lowered, perhaps to negligible proportions, by taking advantage of the slow mixing and the stratification of the ocean waters, and of the fact that nearly all organisms of direct importance to man live in the upper one or two hundred meters.

It must be remembered, however, that unlike the waters, the animals of the sea move vertically at relatively high speeds. The possibilities of vertical transport of radioactive substances between levels by marine animals need careful investigation.

Appendix. A comparison of fission product isotopes in the ocean with the amounts of radioactive nuclides present assuming 10^{11} megawatt-hours of nuclear power production and subsequent oceanic disposal

Element	*Radioactive nuclide*	*Amount of element in oceans in megatons*	*Curies of nuclide disposed to ocean*	*Nuclide half-life in years*	*Tons of nuclide*	*Specific activity, c/gm*
Pm	Pm^{147}	–	9.8×10^{11}	2.6	–	
Nb	Nb^{95}	1.4	7.0×10^{10}	3.65	66	5×10^{-8}
Ce	Ce^{144}	560	3.1×10^{10}	0.79	9.6	1.8×10^{-5}
Ru	Ru^{106}	0.014	1.8×10^{10}	1.0	5.2	1.3
Sr	Sr^{90}	10^7	6.8×10^{10}	20.	340	6.8×10^{-9}
Cs	Cs^{137}	700	6.0×10^{10}	33.	750	8.6×10^{-5}
Kr	Kr^{85}	420	3.3×10^{9}	94.	7.3	7.9×10^{-4}
Sm	Sm^{151}	56	2.0×10^{7}	73.	0.7	3.6×10^{-6}

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Contribution from the Scripps Institution of Oceanography, New Series No. 795, supported under a contract with the Air Force Cambridge Research Center

Wind stress on water: an hypothesis

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Q. Jour. Roy. Met. Soc.
Vol. 81, 349 July 1955
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Wind stress on water: an hypothesis

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(Communicated by T. W. Wormell. Manuscript received 25 February 1955)

SUMMARY

The form drag of wind on an irregular surface is found to equal the product of U^2 (U is anemometer wind-speed) and a function of the two-dimensional spectrum of this surface. For a solid surface this function is, of course, independent of U and the form drag is proportional to U^2, as observed over land. Over water, Neumann's frequency spectrum and the glitter measurements by Cox and Munk make this function proportional to U, and hence the form drag proportional to U^3. The computed form drag is not far out of line with measurements by Van Dorn and others.

The dependence of form drag on the 'beam-width' and frequency spectrum of the surface roughness is discussed. The essential roughness statistic comes close to being the mean-square *slope* of the surface, rather than being related to wave height or some other roughness *length*, as usually assumed. The slope statistics are governed by the high-frequency part of the wave spectrum, and this feature accounts for the pronounced reduction of form drag by surface 'slicks,' and the relatively small effect of a limited fetch. The total drag, $c_1 U^2 + c_2 U^3$ (skin friction + form drag), must be larger at very high winds than if it followed a U^2 law, as usually assumed.

1. INTRODUCTION

The problem of wind stress on water plays an essential part in studies of ocean circulation and storm tides, and of the momentum balance of atmospheric circulation. The present note is an attempt to connect results from recent experimental determinations of wind stress with results from measurements of wave statistics. The idea was already inherent in an early paper by Jeffreys (1925), but he was unable to achieve quantitative agreement, largely on account of dealing only with a single-frequency wave system. A more recent treatment by Kapitza (1949) does not go beyond the work of Jeffreys, as far as I can see. Francis's experiments (1951, 1954a, 1954b) have been most stimulating, and much of what will be said here is already implied in Section 5 of his last paper.

2. WIND STRESS

Our empirical knowledge of wind stress is based largely on measurements of (1) the tilt, or 'set-up,' of a water surface under wind action, and (2) the deviation from geostrophic flow of the wind near the surface. In the past these two methods have given quite different results. The situation has now changed. In an important paper presented at the UGGI meeting in Rome, Charnock was able to point out that a shortcoming in the past use of method (2) can account for the discrepancy. Nearly all the 'better' data are now reasonably consistent. They indicate that the stress increases with the 'anemometer' wind-speed U more rapidly than U^2 but less rapidly than U^3. Over land, the U^2 law appears to be satisfactory. This is essentially also the conclusion reached by Francis (1954b) in a recent summary of all measurements by method (1), and by Groen (personal communication) from measurements over the Wadden Sea.

Van Dorn's (1953) measurements by method (1) give a reasonable picture of the present state of affairs. Curve B, Fig. 1, represents the stress on the natural surface; line A refers to conditions after the application of a detergent has greatly reduced the 'roughness' of the water. The simplest interpretation, but not the only one, is to associate

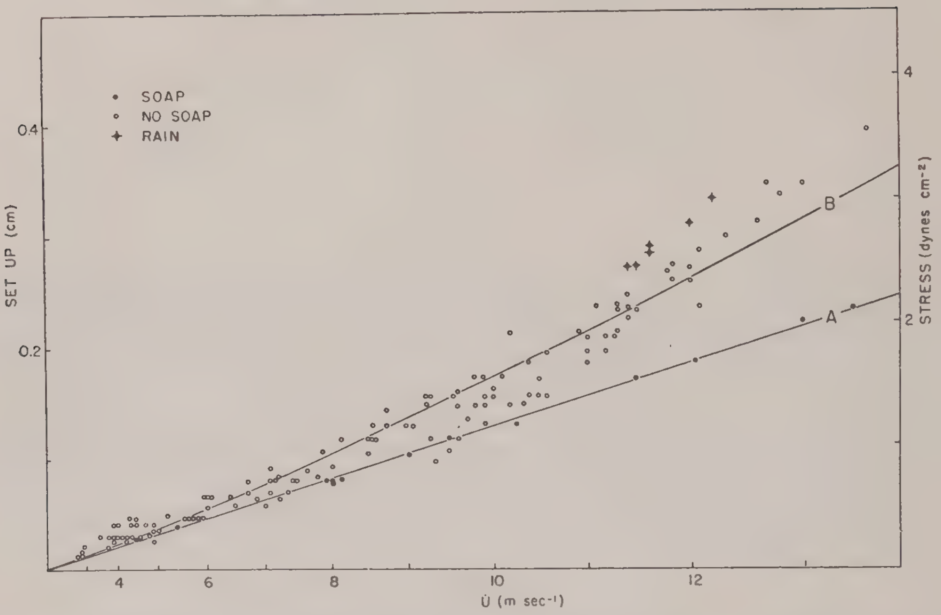

Figure 1. Van Dorn's measurements in Mission Bay model-yacht pond. The abscissa is linear in U^2, where U is the wind speed at the 10-m level. The conversion of the measured values of ' set-up ' (left scale) to stress (right scale) presumes a negligible stress on the bottom, as found by Van Dorn.

the quadratic stress relation (curve A) to the skin friction, τ_s, and to assign the incremental stress between curves A and B to the form drag, τ_f, against the waves. An increment in stress associated with the development of waves has also been observed in the laboratory (Keulegan 1951; Francis 1951, 1954a). According to the usual law for turbulent flow over polished plates

$$\tau_s = c\,\rho\,U^2 \qquad . \quad . \quad . \quad . \quad . \qquad (1)$$

where ρ is air density. Van Dorn obtains $c = 0{\cdot}0025$ and $0{\cdot}0010$ from curve A, depending on whether U is measured at 1 m or 10 m. Curve B has been drawn by assuming the incremental set-up to be given by

$$\tau_f = c'\,\rho\,(g\nu)^{-1/3}\,U^3, \qquad c' = 0{\cdot}68 \times 10^{-6} \qquad . \quad . \quad . \qquad (2)$$

where ν is the kinematic viscosity of the fluid. The factor $(g\nu)^{-1/3}$ has been introduced from dimensional considerations.* The above value of c' was computed by the method of least squares, and refers to the anemometer at 10 m. The standard deviation of the observed τ_f from that given by (2) is 0·23 dynes cm^{-2}.

Following Keulegan (1951), Van Dorn fitted his data by assuming the incremental stress to vary as $(U - U_0)^2$, where U_0 is an empirical constant, the ' formula ' velocity. This gives a somewhat better fit than the cubic law, which is seen to be low at high winds, and high at moderate winds. The cubic law was selected because it follows from the hypothesis to be discussed in this paper.

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* The dimensionless number $U_{\min}\,(g\nu)^{-1/3}$, for the least wind to maintain waves against viscosity, appears in Jeffreys's (1925) sheltering hypothesis. Experiments with water ($\nu = 0{\cdot}01$ cm² sec⁻¹) and a concentrated sugar solution (0·018 to 0·06 cm² sec⁻¹) by Keulegan (1951) and with oil (2·51 cm² sec⁻¹) by Francis (1954a) are consistent with $U_{\min}$ proportional to $\nu^{1/3}$.

3. Sheltering hypothesis

Let $h(x, y, t)$ designate the elevation of the sea surface, and $p(x, y, t)$ the pressure at the surface. In both cases we refer to departures from mean values. The components of the normal stress for small surface slopes are $p \cdot \partial h/\partial x$, $p \cdot \partial h/\partial y$, and $-p$. Their mean values,

$$\tau_x = < p \cdot \partial h/\partial x >, \quad \tau_y = < p \cdot \partial h/\partial y >, \quad \tau_z = 0 \quad . \quad . \quad (3)$$

define the average stress due to the normal pressure, i.e., the components of the form drag τ_f. For a statistically uniform surface $< >$ designates either space or time averages.

To proceed further we must know something about the distribution of pressure over a rough surface. The principal evidence comes from wind-tunnel experiments with a *solid* sinusoidal bottom, $h = a \cos kx$, and the wind blowing along the x-axis. Suppose we measure p along the wave profile by a series of pitot tubes, and represent the resulting observations by a Fourier series

$$p(x) = A_1 \cos kx + A_2 \cos 2kx + \dots$$
$$+ A_1' \sin kx + A_2' \sin 2kx + \dots$$

Then since $\partial h/\partial x$ varies as $\sin kx$, the only term that will contribute to τ_x is the one in $\sin kx$. This term is out of phase with the wave profile. The irrotational theory (Lamb 1932, p. 373) gives only an in-phase pressure variation

$$-\rho U^2 k a \cos kx \quad . \quad . \quad . \quad . \quad (4)$$

with a minimum in pressure over the crests, and a maximum over the troughs. The required term is therefore outside the scope of the irrotational theory. But in a turbulent regime such a term can be found, and is in fact prominent. It is associated with the phenomenon of the lee vortex. The following passage is taken from Jeffreys's (1925) paper :

> Water flowing past a sphere does not in general flow all round it; the particles that strike the front of the sphere leave it soon after they have passed the centre, and the region behind the sphere is occupied by eddying liquid with little or no systematic motion relative to the sphere. By analogy one may suggest that if waves are once formed on water, the main air current, instead of flowing steadily down into the troughs and over the crests, merely slides over each crest and impinges on the next wave at some point intermediate between the trough and the crest. The region sheltered from the main air current contains an eddy with a horizontal axis, while smaller eddies exist along the boundary between this eddy and the main current. If such a theory is correct, the pressure of the air will be greater on the slopes facing the wind than on those away from it; for the deflexion of the air upwards when it strikes the exposed slopes implies a reaction between the air and the water.

By analogy with the problem of the thrust of a current against a plane lamina inclined to the direction of flow, Jeffreys infers that the reaction (to be designated by p) is proportional to the air density, the square of the wind speed, and the surface slope :

$$p = s \rho U^2 \cdot \partial h/\partial x = - s \rho U^2 k a \sin kx \quad . \quad . \quad . \quad (5)$$

Jeffreys calls s the 'sheltering coefficient.' By the preceding argument it must be less than unity : we shall find it to be of the order of a few per cent. A comparison of expressions (4) and (5) shows that the sheltering is out of phase with the irrotational term and only s times as large. But this relatively small component in the pressure variations over the waves is the one important to our problem.

In the final analysis the assumed form of expression (5) must rely on experimental evidence. The appeal to the extensive experimental work with inclined *isolated* laminae is not altogether convincing, because there one includes also the effect of circulation *around* the laminae. The critical experiment of measuring pressure variations along the profiles of water waves has not yet been accomplished. Wind-tunnel experiments with *solid* corrugated surfaces have been performed by Stanton *et al.* (1932) and Motzfeld (1937) (see Table 1). In three out of five of Stanton's experiments the sheltering term actually exceeds the irrotational term, and yet s is small. This is contrary to expectation. Individual values of s vary widely, and they do not lend any support to the law assumed by Jeffreys. Motzfeld's results, on the other hand, are definitely encouraging.* To a first approximation Motzfeld finds low pressure at the crests and high pressure over the troughs, as predicted by (4). In addition, there are small but consistent deviations which are roughly in accord with (5), as indicated by the relative constancy of the s-values computed from his data for runs (a)-(c) (Table 1). Yet between runs (a) and (b) the height was doubled, and between (a) and (c) the length was cut in half. The coefficient was markedly higher for experiment (d), for which the wave crests were sharply edged. The latter experiment was carried out for four different values of wind speed, yet s remained the same, in accord with the assumed quadratic dependence of the pressure term on wind speed.

The critical dependence of s on the shape of the crest indicates that Jeffreys's sheltering expression (5) cannot be complete, and that it should depend on other factors (curvature at crest, perhaps) as well. Experiments by Fromm (1923) with flow through roughened pipes indicate also a possible role of skewness. Using a 30°-60° saw-tooth roughness, he found a drag twice as great, when the flow was directed against the steep slopes, as when it was directed oppositely. The following development is certainly weakened by having to ignore these circumstances. Motzfeld's result is hardly unexpected, inasmuch as one is accustomed to find a more-pronounced flow separation in the lee of sharp edges than in the lee of smoothly-curved surfaces. Perhaps the tiny corrugations just leeward of the crests of wind waves (Munk 1954) have a similar effect to the sharp edges in Motzfeld's sheet-metal waves; this could explain why the waves fail to be *regenerated* when the corrugations are smoothed by the addition of a detergent (Van Dorn 1953). The hypothesis is that the smoothing leads to a smaller value of s, and a corresponding reduction of energy input into waves by normal pressures. The suggestion is due to Charles Cox (personal communication).

TABLE 1. Results from wind-tunnel measurements

		a (cm)	λ (cm)	U (cm sec^{-1})	s
Stanton	(a)	1·1	10·8	325	0·036
	(b)	1·1	10·8	470	0·047
	(c)	2·2	21·6	330	0·068
	(d)	2·2	21·6	580	0·090
	(e)	1·5†	7·6	1400	0·006
				Average	0·049
Motzfeld	(a)	0·75	30	110	0·034
	(b)	1·5	30	110	0·024
	(c)	0·72	15	110	0·030
	(d)	1·0‡	15	63, 116, 139, 178	0·098, 0·098, 0·098, 0·098
				Average	0·047

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* This was pointed out to me by Capt. I. T. A. Hunt (USA). Francis has written to me that inasmuch as Motzfeld's measurements were rather near to the upwind end of the tunnel it is possible that the flow pattern was affected by entry conditions.

† Performed in a different wind tunnel from other measurements.

‡ Sharp 120° crests; other measurements over sinusoidal waves. The value of s was computed allowing for the sharp crests according to equation 6 (3) of Jeffreys (1925); for sinusoidal waves of equal length and height one obtains $s = 0{\cdot}107$ instead of 0·098.

4. SHELTERING HYPOTHESIS FOR WATER SURFACE

The next problem is to extend the 'sheltering' law (5) to a water surface. The simplest case is that of a sine wave progressing in the x-direction. Accordingly we write

$$h = a \cos (kx - \omega t) \qquad \text{(6)}$$

where the wave number, k, and the frequency, ω, are related according to the usual deep-water theory,

$$\omega^2 = g\,k \qquad \text{(7)}$$

The phase velocity is then given by

$$C = \omega/k = g/\omega \qquad \text{(8)}$$

The obvious procedure is to write

$$p = \pm\, s\, \rho\, (U - C)^2 \cdot \partial h/\partial x \qquad \text{(9)}$$

in the place of (5), with the sign depending on whether U is greater or less than C. This is what Jeffreys has done. The sheltering pressure is now proportional to the square of the wind speed, relative to the moving crests. The form drag, according to Eq. (3), equals

$$\tau_f = \tau_x = s\, \rho < \pm\, (U - C)^2\, (\partial h/\partial x)^2 > \qquad \text{(10)}$$

But there are difficulties if this procedure is to be extended to the case of several sine waves. In the resulting interference pattern, the quantity C has now no immediately observable interpretation, such as the one given by Eq. (8). We shall reinterpret it as the 'facet velocity.' Consider a facet of water surface at a fixed distance h above the undisturbed water level. The velocity C of this facet is then defined by

$$\frac{dh}{dt} = \frac{\partial h}{\partial t} + C\,\frac{\partial h}{\partial x} = 0 \qquad \text{(11)}$$

The trouble is that C may become infinite at crest and trough, where, according to Eq. (9), this leads to an infinite pressure jump. The mean-square pressure is also infinite. The form drag $< p \cdot \partial h/\partial x >$ remains, however, finite. Evidently the contributions by the infinite pressure jumps to the form drag are small. Only when the wave amplitudes are perfectly steady, that is, when $\partial h/\partial t = 0$, is the infinite pressure jump avoided. Jeffreys was concerned with this singular case.

As an example, suppose the interference pattern gives rise to a profile of slowly varying amplitude,

$$h = a\,(1 + \epsilon\, \omega t) \cos (kx - \omega t),$$

with $\epsilon \ll 1$. Then the pressure pattern is given by (Fig. 2),

$$p = \pm\, s\, \rho\, (U - g/\omega)^2 \cdot \partial h/\partial x$$

except within a small distance $\xi = \epsilon^2/k$ to either side of the crest (or trough), where it is given by

$$p = \pm\, s\, \rho\, (g/\omega)^2\, \epsilon^2\, k\, a\, (k\xi)^{-1}.$$

The average contribution to τ_x by the pressure spikes is only ϵ^4 that of the remaining pressure pattern.

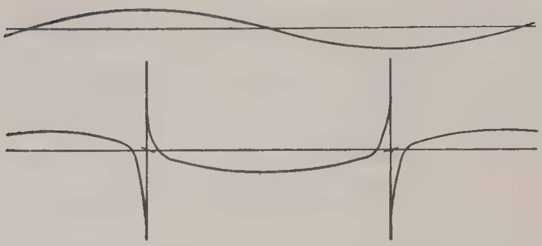

Figure 2. The upper curve is the wave profile, the lower curve the pressure according to Eqs. (9) and (11).

This discussion is not intended to give the reader the impression that the pressure spikes are to be taken seriously. They arise only from the adopted definitions of p and C. What has been shown is that the spikes can be accepted without appreciably affecting the present discussion. An alternative procedure is to introduce a simple modification of Jeffreys's pressure pattern (9), which avoids the infinite spikes, and yet is in accord with experimental evidence :

$$p = s\,\rho\,U\,(U - C) \cdot \partial h/\partial x = s\,\rho\,U \left(U \frac{\partial h}{\partial x} + \frac{\partial h}{\partial t}\right) \qquad . \qquad . \quad (12)$$

The expression in the brackets represents the vertical movement of the water surface as seen by an observer drifting with the anemometer wind.

For the two-dimensional case, we introduce the vector slope ∇h of magnitude $|\nabla h|$ in the direction θ relative to the x-axis. Then

$$C = -\frac{\partial h/\partial t}{|\nabla h|}, \qquad \cos\theta = \frac{\partial h/\partial x}{|\nabla h|}$$

and

$$\tau = < p\,\nabla h >.$$

Taking first the spike pressure, it would seem reasonable to write it in the form

$$p = \pm\, s\,\rho < (U \cdot \nabla h + \partial h/\partial t)^2 \frac{1}{|\nabla h|} >$$

so that

$$\tau_x = s\,\rho < \left(U \frac{\partial h}{\partial x} + \frac{\partial h}{\partial t}\right)^2 \cos\theta > \qquad . \qquad . \qquad . \quad (13a)$$

$$\tau_y = s\,\rho < \left(U \frac{\partial h}{\partial x} + \frac{\partial h}{\partial t}\right)^2 \sin\theta > \qquad . \qquad . \qquad . \quad (13b)$$

For the revised pressure pattern (12) we write

$$p = s\,\rho\,U\,(U \cdot \nabla h + \partial h/\partial t)$$

and

$$\tau_x = s\,\rho\,U < U \frac{\partial h}{\partial x}\frac{\partial h}{\partial x} + \frac{\partial h}{\partial x}\frac{\partial h}{\partial t} > \qquad . \qquad . \qquad . \quad (14a)$$

$$\tau_y = s\,\rho\,U < U \frac{\partial h}{\partial x}\frac{\partial h}{\partial y} + \frac{\partial h}{\partial y}\frac{\partial h}{\partial t} > \qquad . \qquad . \qquad . \quad (14b)$$

There is, of course, a good deal of arbitrariness in any of these derivations. For example, one could write $U \cos \theta$ instead of U outside the parenthesis in Eq. (14), or define C in terms of the velocity of a facet of constant *slope*. The laboratory experiments do not distinguish between these alternatives, nor between Eqs. (13) and (14), because all of these expressions are equivalent when $\cos \theta$ and $\partial h/\partial t$ are zero. I shall use Eq. (14) because the calculations are then by far the simplest; this avoids also the infinite pressure peaks. Any refinement should await further experimental evidence. But one further remark should be made here. It is nearly certain that the essential results reached in this investigation do not depend critically on whether the pressure varies as $(U - C)^2$ or $U(U - C)$, or in some other similar way.

5. TRANSFORMATION INTO WAVE SPECTRA

The quantities in Eq. (14) can be transformed into a more familiar form. A useful tool is the correlation (or mean displaced product)

$$\psi(a, b, \tau) = <(h(x, y, t)\, h(x + a, y + b, t + \tau)>$$

between the elevations at a position x, y and time t, and at $x + a$, $y + b$, and $t + \tau$. The following identities have been established (for example, Eckart 1953) :

$$-\left.\frac{\partial^2 \psi}{\partial a^2}\right|_{a=b=\tau=0} = < \frac{\partial h}{\partial x}\frac{\partial h}{\partial x} > = \int_0^\infty \int_{-\pi}^{\pi} k^2 \cos^2 \theta\, S(k, \theta)\, k\, dk\, d\theta$$

$$-\left.\frac{\partial^2 \psi}{\partial a\, \partial \tau}\right|_{a=b=\tau=0} = < \frac{\partial h}{\partial x}\frac{\partial h}{\partial t} > = -\int_0^\infty \int_{-\pi}^{\pi} \omega k \cos \theta\, S(k, \theta)\, k\, dk\, d\theta,$$

and similarly for b. Here $S(k, \theta)$ is the wave spectrum (units cm^4); $S(k, \theta)\, k\, dk\, d\theta$ designates the contribution, to the total mean-square elevation, by waves with wave numbers in the interval $k - \frac{1}{2}\delta k$ to $k + \frac{1}{2}\delta k$, and which travel in the direction from $\theta - \frac{1}{2}\delta\theta$ to $\theta + \frac{1}{2}\delta\theta$ relative to the x-axis. Eq. (14) can now be written

$$\tau_x = s \rho U \int_0^\infty \int_{-\pi}^{\pi} [U \cos \theta - C(k)]\, k^2 \cos \theta\, S(k, \theta)\, k\, dk\, d\theta, \quad . \quad . \quad (15a)$$

$$\tau_y = s \rho U \int_0^\infty \int_{-\pi}^{\pi} [U \cos \theta - C(k)]\, k^2 \sin \theta\, S(k, \theta)\, k\, dk\, d\theta. \quad . \quad . \quad (15b)$$

These are the required equations for relating the form drag to the wave spectrum.

6. COMPARISON OF SPECIAL SOLUTIONS WITH OBSERVATIONS

To proceed further we have to specify $S(k, \theta)$.

(a) *Cross-wind symmetry*

One does not ordinarily expect systematic differences between waves moving at some given angle θ to the right and to the left of the generating wind, and this is in fact confirmed by the glitter observations (Cox and Munk 1954). Hence $S(k, +\theta) = S(k, -\theta)$, and the contributions from $+\theta$ cancel those from $-\theta$ in Eq. (15b), so that

$$\tau_y = 0 \quad . \quad . \quad . \quad . \quad . \quad (16)$$

One can imagine some intriguing exceptions. Wherever there are marked changes in wind direction over short distances, such as behind islands, in intense concentrated cyclones, or near storm fronts, the sea may be sufficiently out of alignment with the local wind to produce a stress at an angle with the mean local wind. A similar effect could result from wave refraction in shallow water. Mr. Henry Stommel suggested to me in a letter that the absorption of waves by surface-slick bands and the resulting skewness in wave direction would lead to a drag component into the slick. This in turn would cause a convergence at the slick, as observed, and thereby a maintenance of the slick itself.

(*b*) *Narrow beam, high frequency*

The assumption is that the spectrum is so concentrated in high-frequency waves travelling nearly with the wind, that $\cos\theta \simeq 1$ and $C \ll U$ for all waves that contribute appreciably to the integral in Eq. (15a). Therefore

$$\tau_x = s\,\rho\,U^2\,\sigma^2 \qquad (17)$$

where

$$\sigma^2 = \int_0^\infty\int_{-\pi}^{\pi} k^2\,S\,k\,dk\,d\theta$$

is the mean square slope.* From measurements of sun glitter, Cox and Munk (1954) obtain a linear relation between σ^2 and the 'anemometer' wind U. This relation can be written in the dimensionless form

$$\sigma^2 = b\,(g\nu)^{-1/3}\,U \qquad (18)$$

where $b = 1{\cdot}1 \times 10^{-4} \pm 0{\cdot}1 \times 10^{-4}$. Substituting into Eq. (17) gives

$$\tau_x = s\,b\,\rho\,(g\nu)^{-1/3}\,U^3 \qquad (19)$$

The important feature is that the form drag varies like U^3, whereas the skin friction, Eq. (1), varies like U^2. Hence the total stress increases with wind speed more rapidly than U^2, but less rapidly than U^3, in accordance with Francis's and Charnock's conclusion (Section 2). Over land, the equivalent roughness statistic does not vary with wind speed, and hence the quadratic law should apply.

The next question is whether the computed form drag is of the right magnitude. Comparison of Eqs. (2) and (19) identifies $s\,b$ as the theoretical value of c' under the present assumptions. Jeffreys (1925) suggested a value of $s = 0{\cdot}27$ on the basis of the initial formation of waves. Stanton's and Motzfeld's experiments both yielded average values of about 0·05 (Table 1), but no significance must be attached to the close agreement between the two investigations. Sverdrup and Munk (1947) estimated $s = 0{\cdot}01$ from the observed rate of wave growth. With $b = 1{\cdot}1 \times 10^{-4}$ from the glitter measurements, these three estimates of s yield

$$s\,b = 30 \times 10^{-6}, \qquad 5 \times 10^{-6}, \qquad 1 \times 10^{-6},$$

compared with $c' = 0{\cdot}7 \times 10^{-6}$ from Van Dorn's measurements. The computed values are high, but not too far out of line, and one is tempted to consider more realistic models.

(*c*) *Wide beam, high frequency*

The previous assumption of a narrow beam is not in accord with observations. Allowance for variability in wave direction can be expected to reduce the computed values of τ_x. From the ratio of up/down- to cross-wind components of mean-square slope in a trade-wind sea, Cox and Munk inferred a 'beam width' in excess of 130° for the

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* Eq. (17) follows also directly from Eq. (14a) for $\partial h/\partial t \ll U \cdot \partial h/\partial x$.

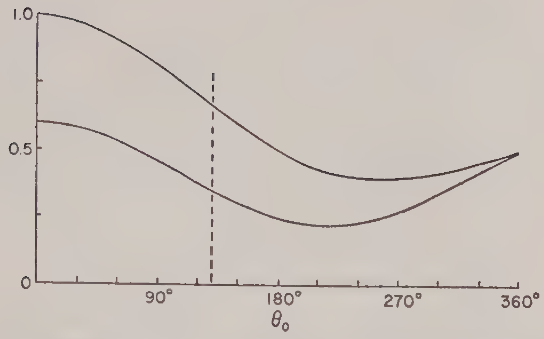

Figure 3. The beam factor $f(\theta_0)$ relating beam width θ_0 to form drag. Upper curve : high-frequency spectrum (Section 6 (c)); lower curve : Neumann spectrum (Section 6 (d)). The beam width of a trade-wind sea is 130°.

relatively short waves that contribute to the slope spectrum. They adopted a model for which

$$S(k, \theta) = F(k) \quad \text{for} \quad -\tfrac{1}{2}\theta_0 < \theta < +\tfrac{1}{2}\theta_0$$

and zero otherwise. The mean-square slope is then given by

$$\sigma^2 = \theta_0 \int_0^\infty k^2 F(k)\, k\, dk,$$

and Eq. (15a) becomes

$$\begin{aligned}\tau_x &= s\,\rho\, U^2\, \theta_0^{-1} \int_{-\frac{1}{2}\theta_0}^{\frac{1}{2}\theta_0} \cos^2\theta\, d\theta \cdot \theta_0 \int_0^\infty k^2 F(k)\, k\, dk \\ &= s\, b\, f(\theta_0)\, \rho\, (g\nu)^{-1/3}\, U^3, \qquad . \quad . \quad . \quad . \quad (20)\end{aligned}$$

where

$$f(\theta_0) = \tfrac{1}{2}\left(1 + \frac{\sin\theta_0}{\theta_0}\right)$$

is a ' beam factor ' (Fig. 3). For a very narrow beam, $f(\theta_0)$ approaches 1, and (20) reduces to the narrow-beam solution (19). For a directionally isotropic sea, $f(\theta_0) = \frac{1}{2}$. For the observed 130° beam, $f(\theta_0) = 0{\cdot}67$ and the computed values of τ_x are two-thirds of those for the pencil-beam pattern.

(d) *Wide beam, Neumann spectrum*

A further reduction results if we discard the assumption of a high-frequency spectrum. The lower frequencies are less effective because their phase velocity approaches the wind speed. The best present estimate for the spectrum of a fully-developed sea is that given by Neumann (1953). For the case of the sharply-bounded directional beam discussed in the preceding section, Neumann's spectrum can be written

$$S_\beta(\beta, \theta) = F(\beta) = \pi^3\, \theta_0^{-1}\, r\, g^{-3}\, U^5\, \beta^4 \exp(-2\beta^2) \qquad . \quad . \quad (21)$$

in the range $-\frac{1}{2}\theta_0 < \theta < \frac{1}{2}\theta_0$, and zero otherwise. Here β is the dimensionless parameter

$$\beta = \frac{C}{U} = \frac{1}{U}\left(\frac{g}{k}\right)^{1/2} \qquad . \quad . \quad . \quad . \quad . \quad (22)$$

which has been called the ' wave age ' by Sverdrup and Munk (1947). The ' wave-age spectrum ' $S_\beta(\beta, \theta)$ has the dimensions cm^2; it is related to the preceding ' wave-number '

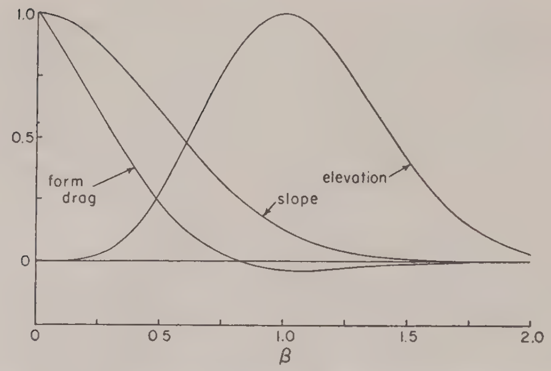

Figure 4. Contributions to the mean-square elevation, mean-square slope and form drag by waves of different wave age β.

spectrum $S(k, \theta)$ according to $S_\beta(\beta, \theta)\, d\beta\, d\theta = S(k, \theta)\, k\, dk\, d\theta$, with β expressed as a function of k according to (22). For short fetches and short duration the energy is concentrated in waves of small β. The spectrum of a fully-developed sea is peaked near $\beta = 1$. The parameter r is a constant with dimension (time)$^{-1}$. By setting

$$r = \frac{4b}{\pi^3 (2\pi)^{1/2}} \left(\frac{g^2}{\nu}\right)^{1/3} \quad . \quad . \quad . \quad . \quad (23)$$

and integrating $k^2 S$ over all values of wave age and direction we recover the empirical relationship, equation (18). All this has been discussed by Cox and Munk (1954).

Eq. (15a) now becomes

$$\tau_x = s \rho g^2 U^{-2} \int_0^\infty \int_{-\pi}^{\pi} \cos\theta\, (\cos\theta - \beta)\, \beta^{-4}\, S(\beta, \theta)\, d\beta\, d\theta$$

$$= s\, b\, f(\theta_0)\, \rho\, (g\nu)^{-1/3}\, U^3 \quad . \quad . \quad . \quad . \quad . \quad (24)$$

where

$$f(\theta_0) = \tfrac{1}{2}\left(1 + \frac{\sin\theta_0}{\theta_0}\right) - \left(\frac{2}{\pi}\right)^{1/2} \frac{\sin \frac{1}{2}\theta_0}{\theta_0}$$

is a beam factor (Fig. 3). Again we have recovered a U^3 law. The beam factor now varies from 0·60 for a pencil beam to 0·25 for a 180° beam pattern. For $\theta_0 = 130°$ and $s = 0{\cdot}27,\ 0{\cdot}05,\ 0{\cdot}01$, one obtains

$$s\, b\, f(\theta_0) = 10 \times 10^{-6}, \quad 2 \times 10^{-6}, \quad 0{\cdot}4 \times 10^{-6}.$$

Van Dorn's observed value, $0{\cdot}7 \times 10^{-6}$, lies between the last two computed values. This is as far as the comparison will be carried. Had we used a different sheltering model, the computed values would be different, but probably not by more than a factor of two.

7. THE CONTRIBUTION TO FORM DRAG BY VARIOUS FREQUENCIES

For the case of a fully-developed sea, the energy spectrum S (Eq. (21)), the corresponding slope spectrum $k^2 S$ (or $\beta^4 S$) and the integrand of Eq. (24) are plotted in Fig. 4. The latter is averaged with respect to θ for a trade-wind sea ($\theta_0 = 130°$). The integrand is actually the co-spectrum of pressure and up/downwind slope. The three curves represent, on an arbitrary scale, the contributions to mean-square elevation, mean-square slope, and form drag, by component waves whose age is in the neighbourhood of β. The noteworthy feature is the large contribution to form drag by the young (or high-frequency) waves. Two consequences of this are examined in Sections 8 and 9.

The extent to which the capillaries and the high-frequency gravity waves contribute cannot yet be determined. If we accept the Neumann spectrum as it stands, then the capillaries can be neglected. In effect this is what has been done here. However, there is some indication that the Neumann spectrum is defective in the capillaries, and it is by no means impossible that both sources are important. In that event Eqs. (21) and (22) must be modified, and the lower limit to the integration in Eq. (24) replaced by $\beta_{\min} = C_{\min}/U$ ($C_{\min} = 23$ cm sec^{-1}). This will result in a substantial reduction of τ_x for low winds.

8. Limited fetch and duration

In Section 6 we have dealt with the case of a 'fully-arisen sea' (Neumann 1953) where it is assumed that all spectral components have attained their equilibrium values. If the wind fetch or duration is small, the effect will be that only the high frequencies (small β) have attained their equilibrium values, whereas the low frequencies have less than their equilibrium values. For prediction purposes Neumann introduces what is essentially an abrupt high-pass filter. This is equivalent to specifying some critical wave age, say β_m, which depends on wind speed, fetch and duration. The spectrum is presumed to be fully developed for $\beta < \beta_m$, and zero for $\beta > \beta_m$.

Suppose now that $\beta_m = 0{\cdot}5$. It will be seen from Fig. 4 that the mean-square elevation is a very small fraction of the equilibrium value. The mean-square slope has more than half its equilibrium value. The form drag, however, has nearly its equilibrium value. The form drag is therefore much less affected by limitations in fetch and duration than the wave amplitude. This accounts, in a qualitative way, for the fact that values of stress by the tilt method (Section 2) for different water bodies have not differed by orders of magnitude, even though the dimensions of the water bodies have.

One could attempt a quantitative treatment by setting an upper limit, β_m, in the integration for τ_x, and then specifying from empirical considerations the dependence of β_m on wind speed, fetch and duration; but this would be carrying the present state of the art too far. We must however point out that such a modification would impair rather than improve, the fit of the computed form drag to the observations, for it would diminish the computed drag at high winds, where it already is too low.

9. Slicks

The opposite example, that of a low-pass filter, is provided by the action of oil or detergent spread on the water surface. Suppose for the moment that the spectrum, for β_m *less* than 0·5, is dissipated by the surface-active agent. This would leave the mean-square elevation virtually unchanged, reduce the mean-square slope by a large factor and essentially eliminate the form drag. In a general way this corresponds to what is observed. But, for moderate and strong winds, β_m is likely to be far smaller, perhaps 0·2, and, according to Fig. 4, a substantial part of the stress should remain, in contradiction to Van Dorn's results. There are however certain complications when the surface contamination entirely covers a limited fetch, and these tend in the direction of a further reduction of τ_x. The contamination wipes out the tiny corrugations on the crests of the waves. Although their direct contribution to the form drag is negligible, they may affect the flow pattern and hence the value of s. A reduction in s leads to a proportional reduction in τ_x, but, in addition, as noted in Section 4, it also apparently leads to a failure for the waves to be regenerated, and this leads to a reduction of the spectrum S, and a further reduction in τ_x.

10. Discussion

In this paper two experimental measurements have been related; those dealing with wind stress (in particular, form drag); and those dealing with the wave spectra. The procedure is somewhat analogous to the derivation of drag coefficients in engineering problems. This is not going back to fundamentals ! But neither has the drag coefficient of a simple cylinder been accounted for from fundamental principles.

The starting point is a sheltering-type hypothesis for the pressure distribution over a wavy surface. But there is much uncertainty in extending available laboratory evidence for one-dimensional sheet-metal waves to an irregular sea surface. The principal weakness of the present treatment is, I think, the assumption that the pressure drop at a point in the lee of a wave crest depends only on the slope *at that point*. It may turn out that the sheltering from upwind waves is an important factor. One then has to go to a more complicated statistics, involving correlation between slope at one point and elevation at another. Progress will not be easy, and further experimental work is essential, and could be rewarding.

There may also be an opportunity of extending the present method to other surfaces with random roughness, provided these surfaces are ' analytical.' Much of the present evidence of drag on rough surfaces is based on experiments with surfaces on which sand grains have been glued; these are poor examples of analytical surfaces.

The present results indicate that the form drag should be proportional to the product of U^2 with a certain statistical description of surface roughness which comes close to the mean-square slope. Over land the surface roughness is independent of wind speed, and the U^2 law applies. Over water the mean square slope increases linearly with U, and hence a U^3 law follows. This would account for the unique behaviour of fluid surfaces. However, the agreement is only fair, and there is definite indication that the computed form drag is low for high winds. The discrepancy is of the same order as the observed increase in form drag caused by rain. It does not seem unreasonable to presume that, on windy days, the flux of spray, up or down, could be as large as the downward flux of rain water. If this is so, then spray picked up by the wind, and accelerated before returning to the surface, represents yet another appreciable mechanism for transfer of momentum from wind to water. With or without spray, the stress at very high winds should be greater than has previously been estimated on the basis of a U^2 law.

Many difficulties remain. At what elevation is the wind to be measured ? What is the effect of lapse rate ? Can skin drag be added to form drag ? Is C the classical phase velocity, or does it exceed this as a consequence of being impelled by the wind ? Does it involve also the orbital velocity of the larger waves present ? But regardless of these difficulties, I am convinced that the form drag is much more closely related to the slope statistics than the elevation statistics. I believe this conclusion is a departure from the usually accepted view.* There one deals with Reynolds numbers, or with roughness coefficients, and in either case a length-parameter is involved which is supposed to be related to wave height. If this were so, then the effect on form drag of a six-foot sea would be equivalent to that of a six-foot tide.* If this were so, one would expect a critical dependence of wind stress on fetch, and no measurable effect due to a detergent, spread on the water surface. If, on the other hand, the high-frequency slope spectrum is the essential element of surface roughness, then the dependence of wind stress on fetch should be slight, as observed; and the reduction by a slick should be considerable, again as observed.

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* But Neumann (1949) and Francis (1954b) have stated that the drag is caused by the small ripples. Francis (1951) also found that high but relatively long waves, generated by a plunger, did not appreciably increase the set-up from wind blowing over water.

ACKNOWLEDGMENTS

I am particularly grateful to Carl Eckart, Charles Cox and Roger Revelle for critical discussions. The research carried out was supported under a Contract with the Air Force Cambridge Research Center.

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RATE OF DEPOSITION SHOWN BY RELATIVE ABUNDANCE OF FORAMINIFERA

BY

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Reprinted for private circulation from
The Bulletin of the American Association of Petroleum Geologists
Vol. 39, No. 8, August, 1955

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BULLETIN OF THE AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS
VOL. 39, NO. 8 (AUGUST, 1955), PP. 1594-1600, 4 FIGS.

RATE OF DEPOSITION SHOWN BY RELATIVE ABUNDANCE OF FORAMINIFERA[1]

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La Jolla, California

ABSTRACT

Estimates of the percentage by volume of Foraminifera in cores from seven deep borings in San Antonio Bay, Texas, were made and curves of these percentages *versus* depth were drawn to 55 feet. It was assumed that production of Foraminifera was at a constant rate and therefore that the rate of total sediment deposition was inversely proportional to the percentage of Foraminifera at any depth. Based on this assumption, depositional rates were computed at depth intervals of 2½ feet. A Carbon-14 dating at 55 feet and the average percentage of Foraminifera throughout the 55-foot column were used as a basis for the calculations. Although the basic assumption of constant production is not universally justified, it may be reasonable within some environments of fine clastic sediment and is apparently valid in San Antonio Bay. Calculations based on this assumption show good agreement with Carbon-14 datings at various depths.

The curve of rate of deposition *versus* time drawn from these calculations shows a large variation in rate, with a maximum of 4.7 feet per century at −6,900 years, decreasing to a minimum rate of 0.2 foot per century from −3,100 to −4,100 years. This is followed by a gradual increase to about 0.7 foot at present.

INTRODUCTION

In the fall of 1953 a program of deep borings was undertaken in the Rockport, Texas, area by the Scripps Institution of Oceanography under the sponsorship of the American Petroleum Institute Project 51.[3] Among the borings, six were in the recent sediments of San Antonio Bay (Fig. 1, XS 388, XS 386, XS 384, XS 383, XS 382, XS 381) extending to depths ranging from 63 to 80 feet. Cores from these borings, along with many others were subjected to coarse-fraction analysis in which estimates of important components of the coarse fraction were made by F. P. Shepard and the writer. The percentage by volume of Foraminifera in the sample is one of the principal components estimated.

Upon completion of preliminary estimates on 68 samples from various depths in these six cores, it was noted that the abundance of Foraminifera in each of the cores seemed to show similar fluctuation with depth. F. B Phleger (personal communication) has suggested that the abundance of live *versus* dead Foraminifera in recent sediment might in some conditions be an indication of the present rate of deposition of the sediment. With this in mind, it seemed reasonable that fluctuations in total number of Foraminifera within a unit of bulk sediment might be used to give an approximate relative rate of deposition in an ancient sediment.

The purpose of this paper is to present the methods whereby rate of deposition was calculated from the percentage of Foraminifera and to discuss the significance of the findings.

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[1] Contributions from the Scripps Institution of Oceanography, New Series, No. 797. This investigation was supported by a grant from the American Petroleum Institute, Project 51. Manuscript received, April 7, 1955.

[2] Scripps Institution of Oceanography, University of California. The writer acknowledges the valuable assistance of F. P. Shepard in compiling data for, and in the preparation of, this manuscript. Suggestions by F. B Phleger and E. L. Hamilton have also been of considerable help. The assistance of D. M. Poole, Harry Lusk, and J. R. Moriarty is also appreciated.

[3] Shepard and Moore (1955) give a general discussion of the results from these tri-dimensional studies.

METHODS

In order to get a composite curve for Foraminifera abundance plotted against depth the following procedure was used. Curves of estimated percentages of Foraminifera plotted against depth in the hole were drawn for each boring.

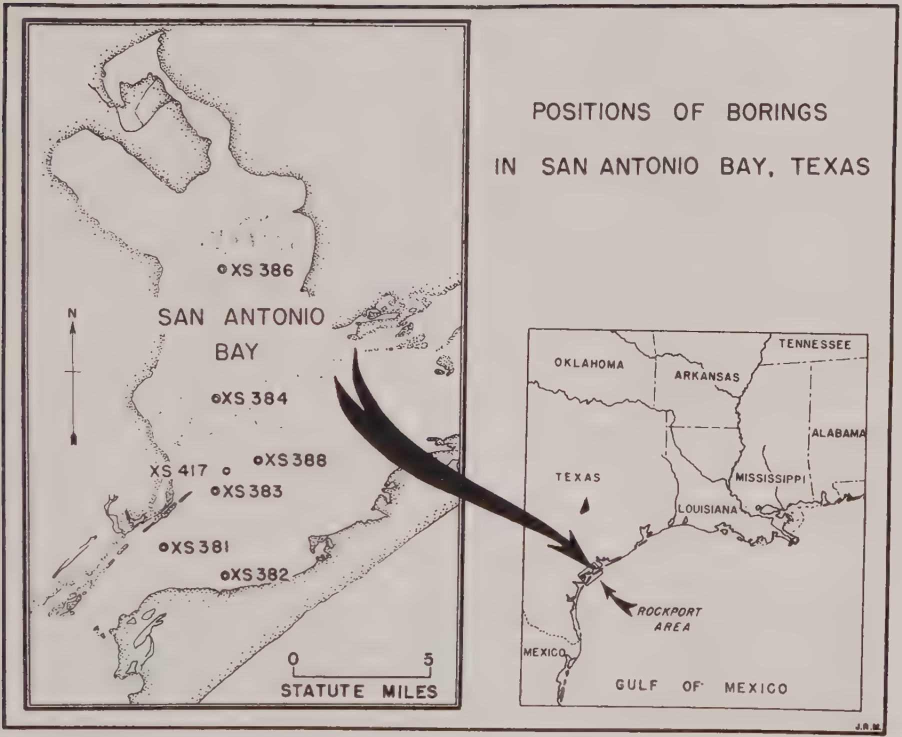
POSITIONS OF BORINGS
IN SAN ANTONIO BAY, TEXAS
N
SAN ANTONIO
BAY
XS 386
XS 384
XS 417
XS 388
XS 383
XS 381
XS 382
0
5
STATUTE MILES
OKLAHOMA
ARKANSAS
TENNESSEE
ALABAMA
MISSISSIPPI
TEXAS
LOUISIANA
ROCKPORT
AREA
MEXICO
GULF OF MEXICO
J.R.M.

FIG. 1.—Area of investigation and positions of borings. Guadalupe River delta shown in upper San Antonio Bay.

A depth of 55 feet was used for the curves in order to allow the use of all six of the deep borings in evaluating the data. By use of these curves, a median curve was drawn, with a $2\frac{1}{2}$-foot depth interval for plotting. In order to check this median curve a continuously cored hole was made to a depth of 24 feet in San Antonio Bay near the other borings (Fig. 1, XS 417) and the Foraminifera content studied in detail. These percentages were comparable with the median curve and were used to make minor corrections in order to increase its reliability. The percentages of Foraminifera in the original deep borings and in the detailed study are shown in Figure 2 with an inset of the final composite curve. Relative rates of deposition can be computed from this composite curve. Absolute rates of deposition could not be ascertained, however, until the age of the sediment at a given depth was known. Fortunately, Carbon-14 datings of oyster shells from the cores at several depths had been made for the project by the Magnolia Petroleum Company's Field Research Laboratories. Figure 3 shows a best-fit (by eye) straight line drawn through the lower Carbon-14 points in order to find the most probable age at 55 feet, which could be used as a basis for the calculations of absolute rates of deposition from the Foraminifera percentages.

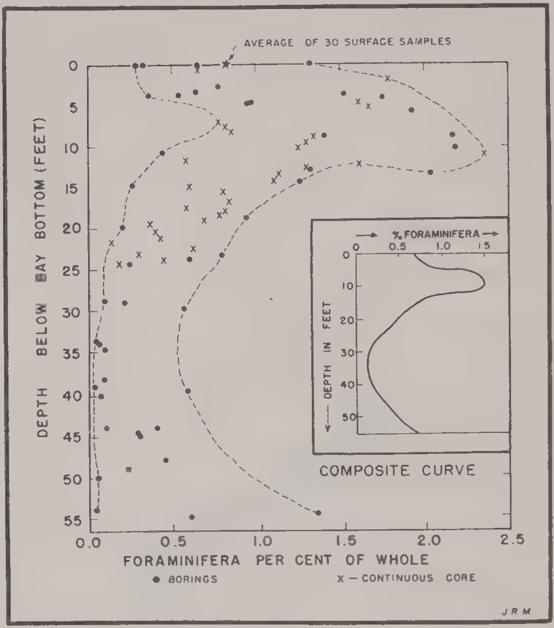

FIG. 2.—Foraminifera, computed as percentage of whole sample, plotted against depth in feet below bay bottom. Dashed lines show maximum and minimum curves. Inset is composite curve computed as median of curves from six borings and slightly modified to satisfy data from detailed sampling.

Calculations of rates of deposition from Foraminifera abundance involve the basic assumption that the rate of production of Foraminifera has been constant in the past, and that variations in Foraminifera abundance are therefore the result of variations in rate of deposition of clastic detritus. The validity of this assumption is discussed later in an evaluation of the method. If this assumption is true, then the total rate of deposition is inversely proportional to the numbers of Foraminifera in the sediment, or:

$$\frac{N_1}{N_2} = \frac{R_2}{R_1}$$

where N equals the percentage of Foraminifera in the sediment and R equals the rate of deposition. To calculate the rate at various points along the curve in which depth is plotted *versus* abundance of Foraminifera, an average rate was computed, by using 7,850 years as the total age of the 55 feet of sediment studied. This time, taken from the Carbon-14 data, gives an average rate of 0.70 foot per century. The average percentage of Foraminifera was derived from the median curve in Figure 2 for the total depth of 55 feet and equals 0.47 per cent. Therefore, in order to calculate rate of deposition at any point (R_o) along the percentage Foraminifera curve:

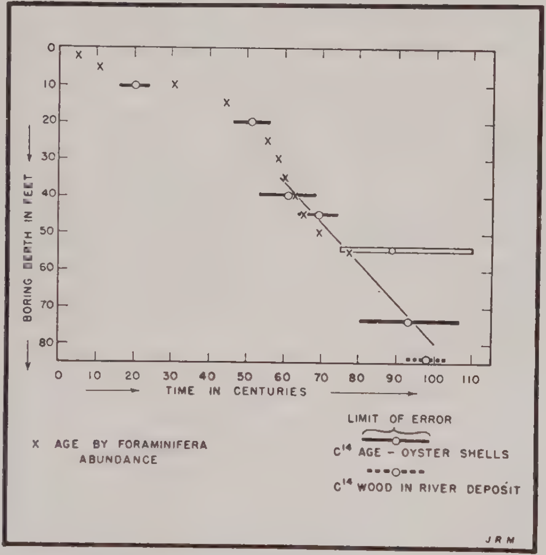

FIG. 3.—Age of sediment at various depths within borings as determined by Foraminifera-abundance calculations and Carbon-14 dating. In drawing the straight line through the lower Carbon-14 points, the dating at 53 feet (shown with white limit-of-error bar) was not given full weight because of analytical difficulties with this sample reported by Magnolia Petroleum Company's Field Research Laboratories.

$$\frac{N_a}{N_o}=\frac{R_o}{R_a} \qquad \text{or} \qquad R_o=\frac{N_a R_a}{N_o}=\frac{0.33}{N_o}$$

where N_a = the average percentage of Foraminifera or, 0.47 per cent, R_a = the average rate of deposition or, 0.70 foot per century, and N_o = the percentage of Foraminifera at the given depth. By this method, the rates of deposition of the sediment were calculated at 2½-foot intervals. This 2½-foot interval was divided by the rate in order to calculate the age of the sediment at the various depths.

EVALUATION OF METHOD

Several objections to the basic assumption of constant rate of Foraminifera production and the methods of estimation of the percentages of Foraminifera can be cited. These are: (1) variations in Foraminifera production might be caused by seasonal, annual, or long-term changes in environment in the bays; (2) productivity of Foraminifera is not constant all over the bay because different assemblages inhabit the different environments of these bays; (3) estimations of volume under the binocular microscope are not sufficiently accurate. All of these objections are valid, but probably none is a sufficient reason to discount the importance of Foraminifera percentages as indicators of rate of deposition in the San Antonio Bay sediments. Variations in production, for example, will unquestionably occur, but they are the result of comparatively short-period fluctuations in the environment. Rainfall, temperature, and salinity are important fluctuations but as they last a relatively short time they become less impressive, and possibly not critical during intervals of several thousand years. Parker (1955) has plotted the salinity variations in the bays near Rockport, Texas, from 1922 to 1952. The variations show short-term fluctuations of considerable amplitude, but over the whole span of years represented they result in a relatively smooth curve. It must be remembered also, that Foraminifera which inhabit a bay near a river mouth such as San Antonio Bay are probably able to withstand considerable variation of temperature and salinity (Shepard and Moore, 1955, give details on the San Antonio Bay area).

Probably the most realistic objection to the assumption of constant production of Foraminifera is the fact that in different environments of the bays different characteristic assemblages of Foraminifera are prevalent. Parker, Phleger, and Peirson (1953) divide the bay into several biofacies on the basis of assemblages of Foraminifera. Therefore, the curves of variation in percentage of Foraminifera with depth could not be expected to be identical in different parts of the bay. On the other hand, any large-scale change in rate of deposition should be felt over the entire bay so that increases and decreases should nearly correspond from one boring to the next. A median curve should therefore be representative of the general rate of deposition throughout the bay. As all the borings used in this study are within the bay facies or bay subfacies of Parker, Phleger, and Peirson, no large discrepancies should exist.

An apparent objection to the validity of these Foraminifera percentages as indicators of rate of deposition is the fact that small percentages such as these can not be estimated with the binocular microscope. Actually the samples have the silt- and clay-size material removed and are sieved so that individual fractions in the sand sizes of the Wentworth size grades are estimated and the percentage of the whole sample is computed from several separate and much larger estimates (details of this method are given in Shepard and Moore, 1954).

A convincing example of approximating the rate of deposition, hence the age of sediments by variation in Foraminifera abundance, is shown in Figure 3 where the age of sediments in San Antonio Bay at different depths are shown plotted as determined by this method and by Carbon-14 dating. Conversely, the close agreement of the ages of sediment from calculations of Foraminifera abundance and from Carbon-14 determinations should serve as evidence of the stability of the rate of production of Foraminifera in an environment such as San Antonio Bay. In spite of this close agreement of radiocarbon and Foraminifera abundance dating, however, it should be emphasized that this is a preliminary study and might be modified by further work on the rate of productivity of Foraminifera.

Certainly no single sediment sample could be expected to give significant results in calculations of rate of deposition by this method. Local variations in rate of supply and removal of sediment are such that Foraminifera could be concentrated by elutriation of a pre-existing soft sediment. Similarly, it is out of the question in areas which are subject to intense current and wave action capable of transporting and concentrating particles of sand size. In summary, it appears that only areas of a single environment in predominantly fine sediments would show significant figures for rate of deposition as established by percentages of Foraminifera.

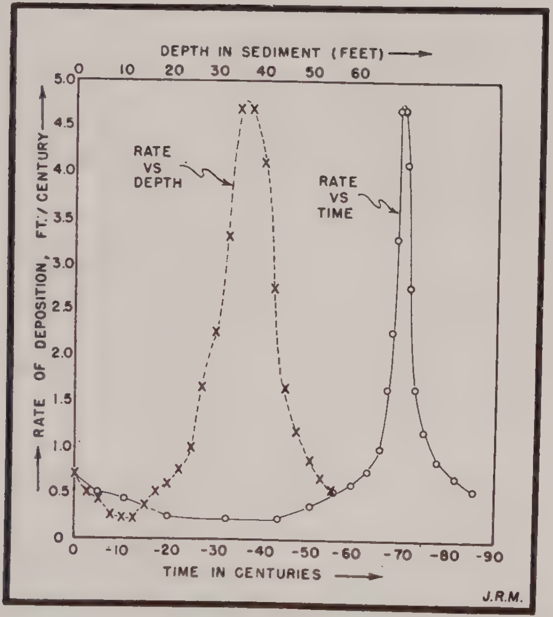

FIG. 4.—Rate of deposition computed from percentages of Foraminifera plotted against depth in sediment and against time in centuries.

RESULTS

The data computed from the composite curve of percentage of Foraminifera with depth were plotted as curves in Figure 4 in order to show the true proportions of rate of deposition *versus* time and depth of burial. These curves indicate a significant build-up in rate between about −8,000[4] and −7,000 years, so that in only about 3,000 years, from −8,000 to −5,000 years, 35 feet of sediment were deposited (neglecting compaction). In strong contrast to this high rate is the rapid drop from the peak at −6,900 years to a uniformly low rate from about −5,000 to −2,000 years during which only about 7½ feet of material were deposited. From that time until the present the curves indicate a uniform increase so that the current rate is figured at about 0.7 foot per century.

These changes in the rate of sedimentation are probably the result of four principal factors: (1) the rate of supply of material into the area by the river, which could have been influenced by the shifting of climatic belts resulting in heavier tropical rainfall in a period of thermal maximum following the last glacial stage; (2) rate of removal is undoubtedly influenced by the water depth since material introduced into a shallow bay is subject to more frequent resuspension as a result of the action of wind-waves, and transportation seaward by wind-driven currents; (3) the shape of the basin of sedimentation might affect the rate at which sediments accumulated in a vertical direction inasmuch as an initially V-shaped river valley would fill much more rapidly near the base of the V than it would after being partly buried even if a uniform volume of sediment was being deposited; and (4) a change in basin shape would also result from a sea-level change inasmuch as the mouth of the river would migrate up its valley with a rise in sea-level and down its valley with a drop in sea-level. This last effectively increases or decreases the distance of a locality from its major sediment source, and thereby causes fluctuations in rate of deposition.

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[4] Years before the present.

(*From the* QUARTERLY JOURNAL OF THE ROYAL METEOROLOGICAL SOCIETY
Vol. 81. No. 349. July 1955).

Correspondence

551.541

'GRAVITY WAVES IN THE ATMOSPHERE'

By EARL GOSSARD and WALTER MUNK

Mr. I. J. W. Pothecary's interesting article (Pothecary 1954) anticipated by a month some of our observations and conclusions (Gossard and Munk 1954).

There are apparently three methods for obtaining the phase velocity of coherent internal waves : (a) by a network of stations, (b) by what we have called the impedance relation (our Eq. 1) and (c) by internal wave theory. Mr. Pothecary used (a) and (b) and we used (a), (b) and (c). We wish, therefore, to point out the close agreement of Mr. Pothecary's observations with (c). He estimates the average height of the stable layer to be 1650 m, and the difference of potential temperature across this layer is about 7°C. Shallow ' water ' internal wave theory (our Eq. 16b) then yields a phase velocity of 20 m sec^{-1}. The other two methods gave 21 and 22 m sec^{-1}.

We have also pointed out that the direction as well as speed of propagation can be obtained from records of a single station by simple vector techniques. Using the first waves of the Abingdon record we find them to be propagating from 240° in good agreement with the orientation of the isochrones obtained from Pothecary's grid of stations.

In our paper we suggested that the observed periods of the oscillations were slightly lower than Brunt's period (1927) for the lapse rate above the inversion, though Martyn (1950) suggested that it should be equal to Brunt's ' just trapped ' period. Examination of the initial-value problem offers a reasonable explanation of the observed shorter periods, however. In spite of the large ratio of wave length to depth, dispersion is found to be important when stability above the inversion is considered, and a maximum group velocity is found which is associated with a wave front (Eckart 1948) where the amplitudes are a maximum.* Let T_F designate the period at this front, and T_B Brunt's period. For a stable lapse, T_B/T_F approaches $(3/2)^{\frac{1}{2}}$ as a limit; for smaller stability the ratio is less, and for an adiabatic lapse it goes to unity as both T_F and T_B become infinite.

It is difficult to apply these considerations to Pothecary's Larkhill sounding because the lapse is so nearly adiabatic. Our estimate for the Larkhill sounding is 0·9 of the adiabatic lapse. This gives $T_B = 20$ min, and $T_F = T_B/1{\cdot}15 = 17{\cdot}5$ min. The observed values were 17, 12·5 and 20 min.

Mr. Pothecary mentions the possibility of gravity waves having the effect of forming or dispersing stratus clouds in air near saturation. An oscillation of solar radiation closely correlated with the oscillation of wind and pressure has been observed in Southern California (Fig. 1). This oscillation is presumably due to oscillations in the thickness of the stratus deck.

We have also found that the oscillations can usually be classed as one or the other of two types depending on duration, character and, apparently, origin. Fig. 2 shows oscillations occurring in fair weather but associated with a storm off shore. Their dying out appeared to be related to the destruction of the Southern California inversion as the storm developed. Apparently this type of oscillation requires storm activity for generation, and a low inversion for propagation. Here, in California, this is a rare combination of events, and so is the occurrence of good examples of these complex oscillations. In the absence of an inversion we seem to find, only, simple pressure surges. Coherence of individual waves seems to extend over about 30 mi, but coherence of wave groups has been noted well over 100 mi.

The other type of oscillation is quite regular and of short duration (Fig. 3). It is a fair-weather phenomenon often associated with a föhn condition which in this area is called a ' Santa Ana.' The oscillations often occur during the night, and usually in the early morning hours as a Santa Ana regime begins to break up. The inversion is low and well developed, leading to low phase velocities and thus large wind oscillations. The neat trace is suggestive of a single, simple source such as a night convection-cell, perhaps triggered by simultaneous föhn heating below and radiational cooling aloft. However, vertical shear across the stable layer is common in these cases and should not be ruled out as a possible source. In Fig. 3 the recording station was located at about the base of the inversion, so that the oscillations are seen in the temperature and humidity traces also.

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* This wave ' front ' is often very abrupt, and in the case of instruments with pen-drag may give the appearance of a pressure jump, as in Pothecary's Farnborough and Abingdon traces.

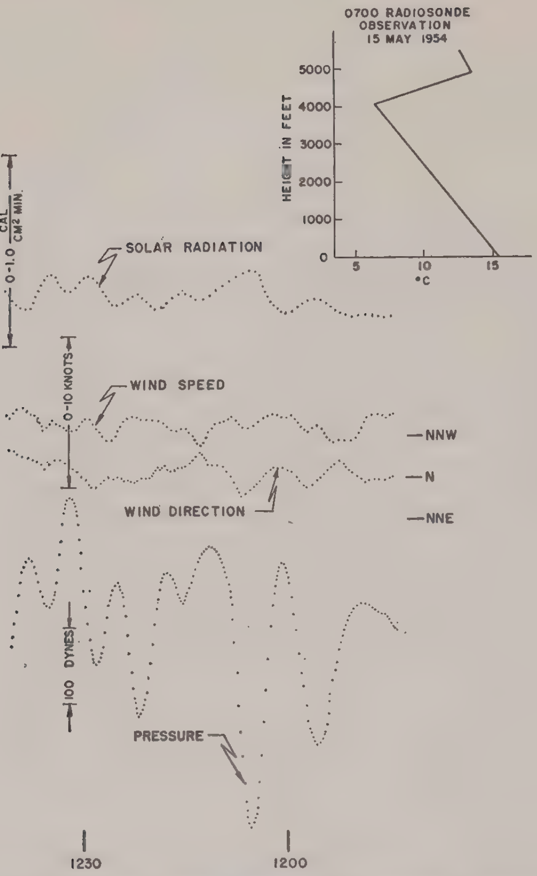

Figure 1. Meteorological record of gravity waves showing also fluctuations of solar radiation through a thin stratus deck.

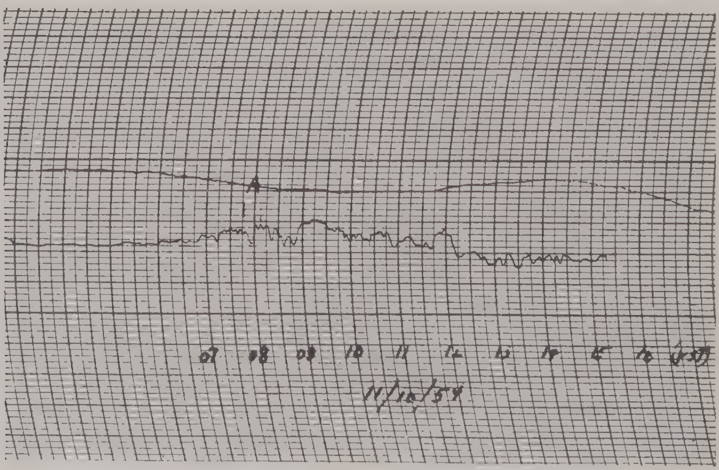

Figure 2. Oscillations associated with a storm centred some 500 mi WSW. of San Diego.

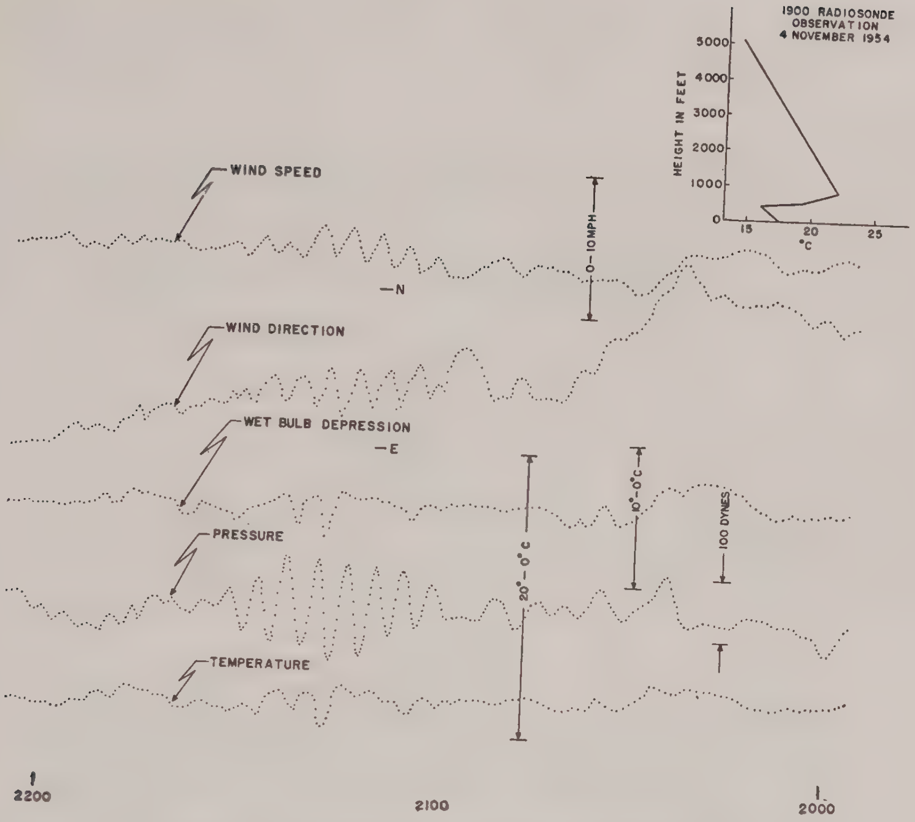

Figure 3. Oscillations associated with a local föhn condition.

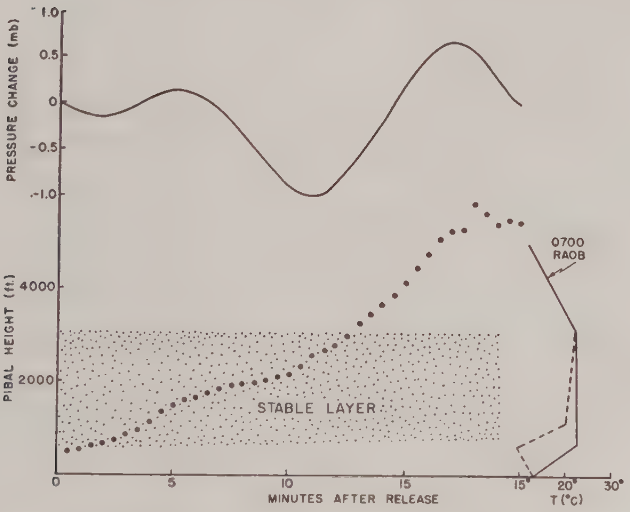

Figure 4. Observations of slow-ascent pilot-balloon through wave 'A' of Fig. 2, together with pressure record. The dashed 'RAOB' curve is the best estimate of the temperature distribution at the time the pibal was taken. The inversion was rising rapidly and its base passed the release point at about 0745 hr.

A slow-ascent pilot-balloon record, taken by a method described by Bellaire (1955), was obtained through wave A of Fig. 2. The plot of balloon height vs. time, shown in Fig. 4, indicates that the oscillation was largely in the fundamental mode.

Added in proof:

While the above note was in press we had the good fortune to observe the waves visually. On 19 May 1955 the temperature and humidity records showed a striking front of marine air travelling inland, followed by a wake of regular wind and pressure oscillations of 7-min period. At the same time a fog bank 500 ft above the sea level and silhouetted against the Ysidro mountains revealed a series of travelling oscillations. The largest oscillation had amplitudes of the order of 200 ft. The outstanding feature was the peakedness of the waves. Their sharp crests separated by long, flat troughs gave the appearance of a long swell in shallow water near the breaking point. The period could be estimated directly and was in accord with the recorded period.

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Contributions from

Scripps Institution of Oceanography,
La Jolla, California, U.S.A.
18 February 1955.

New Series No.798.

REPLY

By I. J. W. POTHECARY

In their original paper (Gossard and Munk 1954) the authors drew attention to a general measure of agreement between the observed period and a period given by $2\pi/s$ where s, the fundamental mode of the longest trapped waves, is derived from $s^2 = g\,\frac{d\,(\ln\theta)}{dz}$ which is an index of the stability above the inversion.

At 03 hr, 6 July 1952, the lapse rate at Larkhill through about 75 mb above the inversion at 830 mb was 16·3°F/km. This corresponds to a value for $\frac{d\,(\ln\theta)}{dz}$ of $3{\cdot}59 \times 10^{-8}$, and gives for s^2 a value of $3{\cdot}52 \times 10^{-5}$.

The derived period of the longest trapped waves is then 1058 sec, which is in good agreement with the values of 1020, 750 and 1,200 sec measured at Farnborough, Abingdon and Croydon respectively.

Meteorological Office,
Dunstable, Beds.
7 April 1955.

Volume 39 Number 8

BULLETIN
of the
AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS

AUGUST, 1955

CENTRAL TEXAS COAST SEDIMENTATION: CHARACTERISTICS OF SEDIMENTARY ENVIRONMENT, RECENT HISTORY, AND DIAGENESIS[1]

FRANCIS P. SHEPARD AND DAVID G. MOORE[2]
La Jolla, California

ABSTRACT

The central Texas coast in the Rockport area has been used as a test area for investigating the characteristics of sediments of protected bays, barrier islands, and of the open Gulf continental shelf. By using a team of sedimentationists, biologists, and chemists, a considerable number of differences have been determined in these three major environments and in subdivisions of each. Influences such as salinity, waves and currents, depth of water, and source material are indicated as the primary controls of the sediment types. In addition to the assemblages of organisms, statistical studies of the constituents of the coarse fraction have been particularly helpful in characterizing the environments.

Among the characteristics which differentiate the sediments of the depositional environments in this area are the following.

1. Bays near river mouths can be identified by their relatively high content of plant fibers, ferruginous aggregates, and ostracods which may predominate over Foraminifera (a relation unique to this environment). Stratification is better preserved than in the other environments in the area. Montmorillonite is the dominant clay mineral and is much more common than in other environments. The $CaCO_3$ content is especially high, being derived as particulate matter from the river.

2. The central and deeper parts of bays are characterized by their lack of stratification, their high clay content, and especially by the abundance of Foraminifera in the coarse fraction (greater than $\frac{1}{16}$ mm.). Parts of these central bay areas are also characterized by the presence of oyster reefs or by the abundance of oyster shells. Montmorillonite and $CaCO_3$ are less abundant than in the upper bays.

3. The lower bays near inlets have sediments with high sand contents (commonly more than 50 per cent) along with a higher content of clay than silt. The faunas show varying admixtures of open Gulf forms with those typical of the bays.

4. The barrier island flats and inlets are characterized by sediments with high sand content but they differ from the lower bays in having more plant fibers. The sediments from the flats have calcareous aggregates and the inlets commonly contain an appreciable proportion of echinoid plates and spines whereas these are rare in bay sediments.

5. The Gulf beaches and dunes consist predominantly of sand, rarely having more than 3 or 4 per cent of silt and clay. This sand is well sorted but almost equally divided between the $\frac{1}{4}$–$\frac{1}{8}$-mm. and $\frac{1}{8}$–$\frac{1}{16}$-mm. sizes. The two environments are distinguished from each other by the consistently greater roundness of the dune sands and by the greater content of shells and Foraminifera in the beach sands.

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[1] Contribution from the Scripps Institution of Oceanography, New Series No. 799. This investigation was supported by a grant from the American Petroleum Institute, Project 51. Manuscript received, March 18, 1955.

[2] Scripps Institution of Oceanography. Reproduced by Permission

6. The nearshore Gulf sediments extending from the barrier island beaches down to depths of about 30 feet are also characterized by a predominance of sand but they differ from the barrier island sands in being concentrated in the $\frac{1}{8}$ to $\frac{1}{16}$-mm. grain size. Glauconite is found in these sediments, whereas it is rare on the barrier islands and very rare in the bays. Shells are rather scarce in this turbulent area.

7. The inner shelf, extending from depths of about 30 feet out to 120 feet, is characterized by sediments with rather considerable amounts of glauconite and echinoids in the coarse fraction. In general shells are scarcer than in the bay sediments. Silt is the dominant size grade, unlike the bay sediments, where clay ordinarily is far more abundant. Lenses of sandy sediment of variable thickness and continuity are common. $CaCO_3$ is distinctly lower than in the bay environments.

8. The outer shelf sediments differ from those of the inner shelf in having a considerable abundance of the easily recognized pelagic Foraminifera, and a higher content of $CaCO_3$. In the area off St. Joseph and Matagorda islands the outer shelf has a high clay content and very little sand but sand is more abundant on the northeast.

By using these environment indicators and assemblages of fossils, it has been possible to differentiate the depositional environments of deposits found in a series of borings made to maximum depths of 85 feet in the bays, 65 feet on the barrier islands, and 60 feet on the delta of the Guadalupe River. It was found that bay deposits extend to as much as 80 feet under the axis of lower San Antonio Bay before encountering sediments deposited during the time of a late glacially lowered sea-level. Barrier island deposits of the Recent cycle continue to depths of 60 feet under the islands. In contrast, bay deposits comparable with those of the present bays are found under the Guadalupe Delta below depths of 5–8 feet and under the lagoon side of Matagorda Island bay deposits are found below about 30 feet. Sediments from an offshore boring in 42 feet of water furnished by the Humble Oil and Refining Company show about 12 feet of shelf deposits underlain by about 60 feet of barrier island sediments. Carbon-14 determinations by the Magnolia Petroleum Company Field Research Laboratories show that the deeper deposits under the bays are contemporaneous in part with the rise of sea-level following the glacial period and that the sands of the barrier islands began to grow upward at least 6,500 years[3] ago as islands or shoals. Carbon-14 dates also indicated that the protected bay sediments were first deposited about 9,500 years before the present.

Studies of early diagenesis of these central Texas coast sediments have shown that the clays have lost far less water by compaction than have sediments in the deep basins off California, probably because of more rapid deposition in the Texas area. The stiffening of the clays found at depths of 20 feet or more under San Antonio Bay is attributed more to the relative increase of effective porosity than to loss of water. At the greatest depths in the borings the clays show some shaly partings. Chemically there is an increase in the chloride ion content between the overlying water and the surface sediment but only an irregular increase with depth. Sulphate ion shows no net decrease to depths of at least 7 or 8 feet, which is in contrast to the conditions in the California basins.

INTRODUCTION

The purpose of American Petroleum Institute Project 51 has been to establish criteria from the study of recent[4] shallow-water marine and estuarine sediments which can be used as an aid in identifying the environment of deposition of ancient sediments. One of the two areas chosen to initiate this work is described in the present report. This area, around Rockport, Texas, 30 miles northeast of Corpus Christi (Fig. 1), includes a group of shallow connected bays separated from the open Gulf by exceptionally wide barrier islands and a broad relatively smooth continental shelf.

This particular location was chosen for the following reasons: (1) the bays have been relatively free from industrial contamination, particularly San Antonio Bay which lies somewhat to the northeast of Rockport; (2) sample collection grounds are rather easily accessible; and (3) two marine laboratories are located in the area, the Texas Game and Fish Commission at Rockport, and the

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[3] These figures are based on shells and may be a little high, probably not more than a few hundred years.

[4] Referring in general to the top 20 cm. of the sediment.

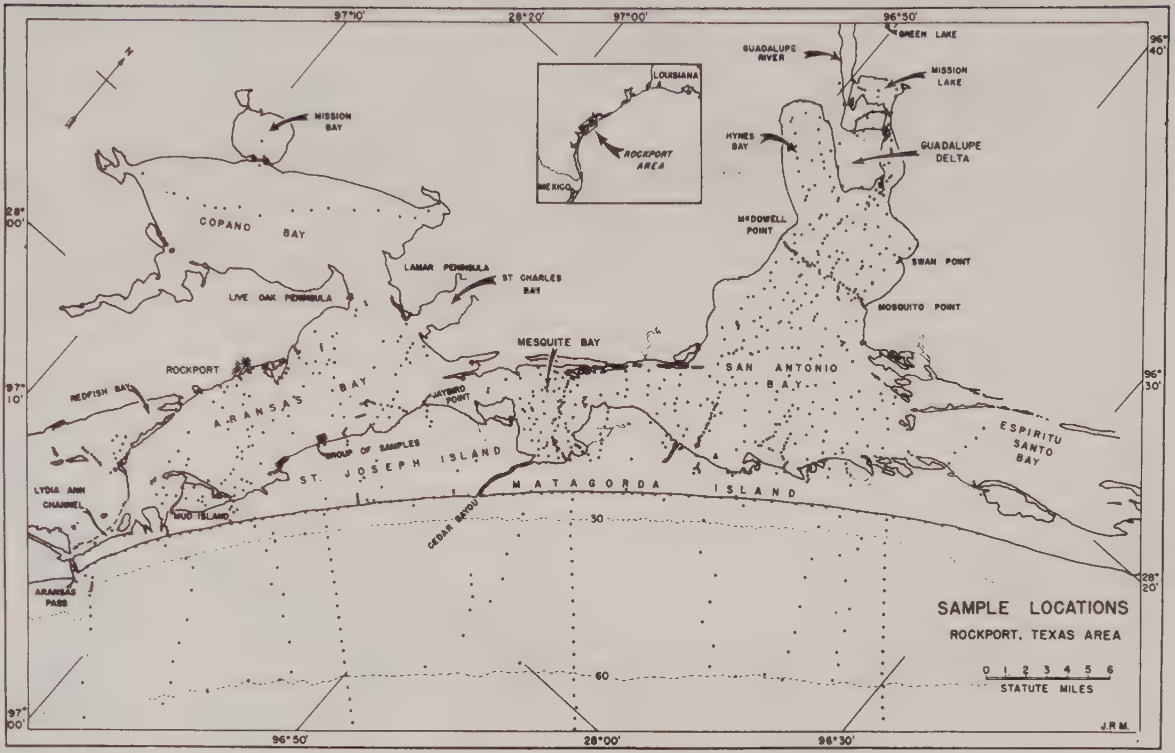
SAMPLE LOCATIONS
ROCKPORT, TEXAS AREA
0 1 2 3 4 5 6
STATUTE MILES
J.R.M.
N
97°10'
28°20'
97°00'
96°50'
96°40'
28°00'
97°10'
96°30'
28°20'
97°00'
96°50'
28°00'
96°30'
LOUISIANA
ROCKPORT AREA
MEXICO
GREEN LAKE
GUADALUPE RIVER
MISSION LAKE
HYNES BAY
GUADALUPE DELTA
McDOWELL POINT
SWAN POINT
MOSQUITO POINT
MISSION BAY
COPANO BAY
LAMAR PENINSULA
ST CHARLES BAY
LIVE OAK PENINSULA
MESQUITE BAY
SAN ANTONIO BAY
ROCKPORT
REDFISH BAY
ARANSAS BAY
HAYNES POINT
ESPIRITU SANTO BAY
GROUP OF SAMPLES
ST. JOSEPH ISLAND
MATAGORDA ISLAND
LYDIA ANN CHANNEL
MUD ISLAND
CEDAR BAYOU
ARANSAS PASS
30
60

FIG. 1.—Showing locations of samples in Rockport area (see also Fig. 2). General location in inset.

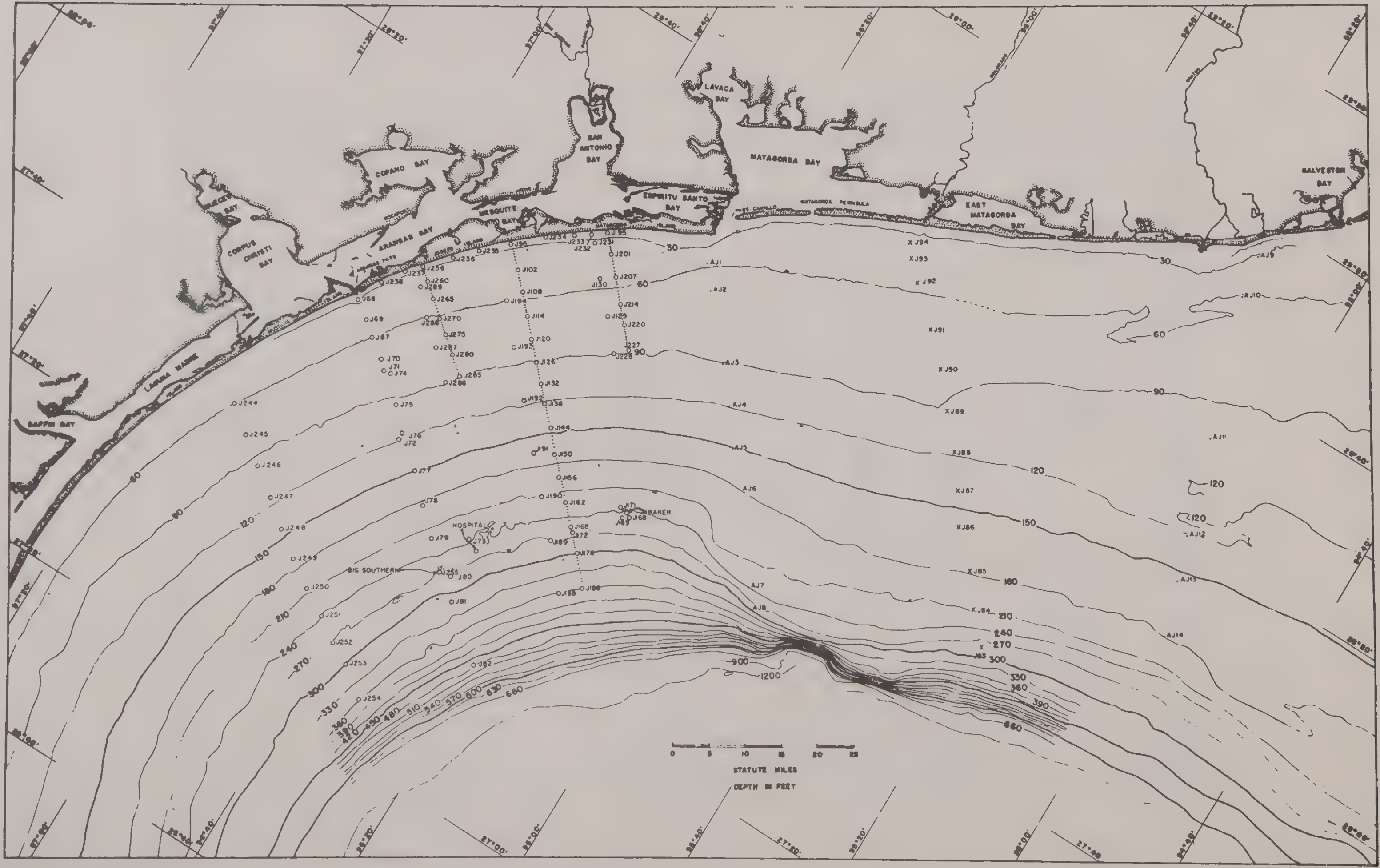
GALVESTON BAY
EAST MATAGORDA BAY
MATAGORDA BAY
MATAGORDA PENINSULA
PASS CAVALLO
LAVACA BAY
ESPIRITU SANTO BAY
SAN ANTONIO BAY
MESQUITE BAY
ARANSAS BAY
COPANO BAY
CORPUS CHRISTI BAY
LAGUNA MADRE
BAFFIN BAY
HOSPITAL
BAKER
BIG SOUTHERN
0 5 10 15 20 25
STATUTE MILES
DEPTH IN FEET
30
60
90
120
150
180
210
240
270
300
330
360
390
660
900
1200

FIG. 2.—Location and number of continental shelf samples. Depths in feet Contour interval, 30 feet.

Institute of Marine Science of the University of Texas at Port Aransas. The laboratory at Rockport offered the use of boat and dock facilities as well as office space. The bays in the area are well suited to the study because they show a range from very low salinity at the mouth of the Guadalupe River in upper San Antonio Bay to high salinity in the lower bays, particularly in Aransas Bay. There are several sources of sediment including rivers, oyster reefs, wind-blown and wave-eroded material from the sandy barrier islands, and wave-débris from low alluvial cliffs along mainland parts of the shore. The continental shelf in this area is favorable as a site of deposition since it has an even slope, broken only near the outer part where a few banks rise about ten fathoms above the general surface. The barrier islands are especially interesting as they contain a variety of depositional environments, including on the Gulf side broad beaches, "beach" ridges, and extensive dunes; and on the bay side overwash fans, low swampy areas, and channels. In addition these islands are among the largest barrier islands on the entire Gulf coast if not in the world. The Rockport area is climatically somewhat intermediate between the semi-arid climate of the Laguna Madre at the south and the humid area at the northeast. As a result of rainfall cycles, deposition representative of several climatic belts can be obtained in the same area. Finally, the fact that sediment studies had been made in areas both on the north and the south by petroleum company research laboratories made it possible, through their generous cooperation, to make some comparative studies and thus to obtain a better general picture of the sedimentation along the Texas coast.

During the 3½ years which have been devoted to the study of the Rockport area, 1,200 sediment samples were collected largely from the bays and continental shelf but also from localities widely distributed over the area (Figs. 1 and 2). In addition, 26 borings were made in the area to an average depth of 45 feet, and many specific observations and collections have yielded data relative to currents, temperature, number and kinds of organisms, and the chemistry and bacteriology of both the waters and the sediments. A staff averaging about eight people has devoted a large part of its time during these years to making field collections and laboratory analyses of the samples. The present report contains only a summary of chemical and biological phases of the work. Several reports giving the results of special phases of these investigations have already been published and others are in press or in preparation.

ACKNOWLEDGMENTS

Many people have been of assistance in gathering and analyzing the data which are used in this report. Primary acknowledgment is extended to the members of Steering and Advisory Committees of API Project 51 for their many helpful suggestions. Two committee chairmen, A. Rodger Denison and Clarence L. Moody, have devoted much time and energy to the development of the project. Marcus A. Hanna, Harold N. Fisk, and Rufus J. LeBlanc have had extensive experience working on the recent sedimentation of the Gulf coast, and contributed from this experience. Particularly helpful suggestions have come from Parke A. Dickey, C. I. Alexander, and N. L. Thomas who have reviewed many manuscripts. The cooperation of the Texas Game and Fish Commission Laboratory, under the leadership of J. L. Baughman and its present director, Cecil Reid, is greatly appreciated. They provided space for equipment and office work during field seasons, and furnished boats for some of the offshore investigations and much of the bay work. One offshore trip was made on the M. V. *Alaska* of the U. S. Fish and Wildlife Service through the cooperation of Albert Collier. The Institute of Marine Sciences of the University of Texas provided its pier to obtain current measurements of Aransas Pass and cooperated in making these measurements. R. M. Norris was in charge of early field collections in the area. M. N. Bramlette, of the Scripps Institution, made field studies which led to the development of a general subaerial geological map of the Rockport area. Bramlette has also made a preliminary investigation of the general petrography of the sediments and has given extensive advice in connection with the development of the project. A committee of ten scientists at the Scripps Institution of Oceanography has met frequently under the chairmanship of Roger Revelle, and this group has been helpful in developing and interpreting various phases of the project.

The grain-size analyses of the cores have been under the efficient direction of D. M. Poole, and he has also made preliminary descriptions and photographs of most of the cores. Information received from special work in sub-projects is discussed briefly in this report. The authors of this information who have or are about to publish more extensive reports will be referred to in the appropriate places. They include: F. B Phleger, Frances L. Parker, and Jean Peirson for the Foraminifera; Fred M. Swain and Doris Malkin Curtis for the Ostracoda; R. H. Parker, E. L. Puffer, and W. K. Emerson for the macro-organisms; George Bien for the chemistry; R. E. Grim and W. D. Johns for the clay minerals; L. R. Wilson and A. E. LeBlanc for the microfossils; D. E. Contois and C. Oppenheimer for the bacteria; D. L. Inman for special-size parameters; D. M. Poole for heavy-mineral studies; and M. A. Beal for roundness studies. Others who have helped extensively include: J. R. Curray, J. W. Durham, J. W. Hedgpeth, R. J. Hurley, H. W. Lusk, T. E. Mahnken, J. R. Moriarty, E. V. Sanborn, D. B. Sayner, P. C. Scruton, and R. Young.

DESCRIPTION OF THE AREA

TOPOGRAPHY OF BAYS AND SHELF

The Rockport area includes four principal bays (Figs. 1 and 3). The largest, San Antonio Bay, is essentially an estuary located at the mouth of the Guadalupe River. This bay has an average width of about 7 miles, and extends into the land for a length of about 18 miles. The seaward boundary is Matagorda Island which forms a wide barrier separating the bay from the Gulf of Mexico. The delta of the Guadalupe River divides the head of San Antonio Bay into two smaller bays: Hynes Bay on the southwest, which is shallow, having few depths exceeding 3 feet, and the narrow Guadalupe Bay on the northeast which has equally small depths. A northern extension of Guadalupe Bay, called Mission Lake, averages about 2 feet deep and is actually not a lake as it is connected with the open bay.

Below the delta, San Antonio Bay deepens gradually except where irregularly shaped oyster reefs produce tracts of shoal water. These reefs are particularly well developed in the central section of the bay. In the lower part of San Antonio Bay there is only one long narrow reef, Panther Reef, which extends from Panther Point on Matagorda Island northward beyond the intracoastal waterway. On the southwest side of the bay, water close to 6 feet deep occurs over fairly large areas.

The depth increases slightly south of the channel so that there is an area west of Panther Reef about 12 miles long and 2 miles wide which has water averaging $6\frac{1}{2}$ feet deep, whereas east of the reef the water averages about 5 feet deep.

Southeast and northwest of San Antonio Bay there are lagoonal areas which vary considerably in width and extend parallel with the barrier islands. Mesquite Bay at the southwest represents a widening of the lagoon, and is connected with the open Gulf by a shallow inlet. This inlet, called Cedar Bayou, has depths of 3–4 feet. Mesquite Bay is shoaler than San Antonio Bay and is generally less than 4 feet in depth. Here, also, there are a few oyster reefs but they are not as pronounced as in San Antonio Bay.

Aransas Bay, another enlargement of the lagoon on the southwest, is the deepest bay of the area. Beyond Long Reef, which essentially divides the bay in two, the depths reach as much as 13 feet, and there is an area about 6 miles long by 4 miles across which is all deeper than 10 feet. Aransas Bay has a long narrow connection with the Gulf through Aransas Pass and Lydia Ann Channel, an inlet which has been established in its present position by jetties. Prior to this construction the inlet was migrating slowly southwest. Two other inlets, called Middle Pass and North Pass (Fig. 4), have been opened twice by hurricanes in recent years.

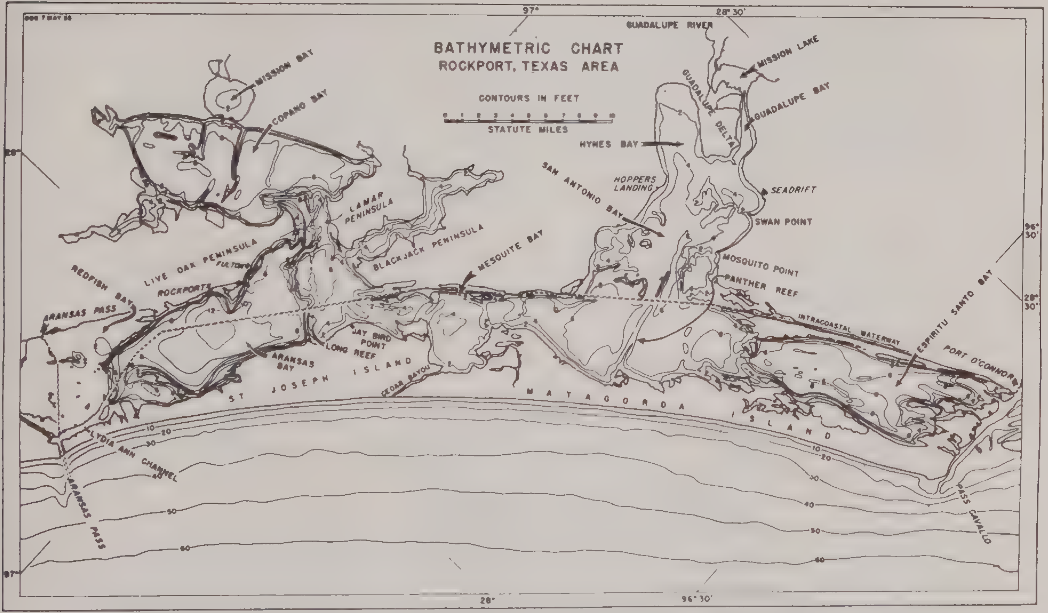
BATHYMETRIC CHART
ROCKPORT, TEXAS AREA
CONTOURS IN FEET
0 1 2 3 4 5 6 7 8 9 10
STATUTE MILES
97°
28° 30'
28°
97°
96° 30'
GUADALUPE RIVER
MISSION LAKE
GUADALUPE DELTA
GUADALUPE BAY
HYNES BAY
SAN ANTONIO BAY
HOPPERS LANDING
SEADRIFT
SWAN POINT
MOSQUITO POINT
PANTHER REEF
INTRACOASTAL WATERWAY
ESPIRITU SANTO BAY
PORT O'CONNOR
PASS CAVALLO
MATAGORDA ISLAND
MISSION BAY
COPANO BAY
LAMAR PENINSULA
BLACKJACK PENINSULA
MESQUITE BAY
LIVE OAK PENINSULA
FULTON
ROCKPORT
REDFISH BAY
ARANSAS PASS
JAY BIRD POINT
LONG REEF
ARANSAS BAY
ST JOSEPH ISLAND
CEDAR BAYOU
LYDIA ANN CHANNEL
ARANSAS PASS
10
20
30
40
50
60
12

FIG. 3.—Bottom topography of Rockport bays and nearshore area. Bay contour interval, 2 feet. Offshore contour interval, 10 feet.

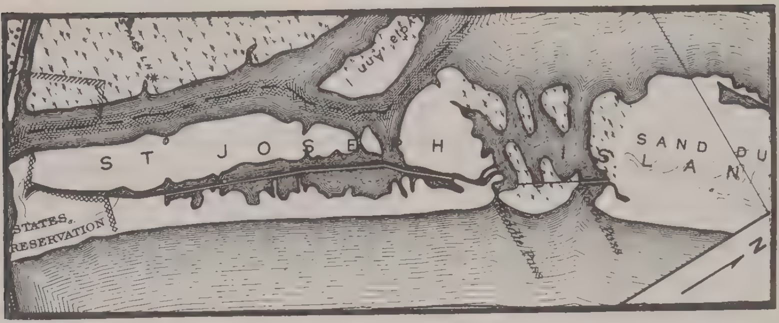

FIG. 4.—Two small inlets in St. Joseph Island opened by hurricane in 1919 and subsequently filled.

Copano Bay, which was only sparsely sampled, is intermediate in depth between San Antonio and Aransas bays, having rather large areas somewhat more than 6 feet in depth. It is marked by a series of living oyster reefs which extend almost at right angles to the elongation of the bay. Redfish Bay, a very shallow bay located southwest of Aransas Bay, has been investigated to some extent during the project. Here most of the depths are about one foot. A considerable part of this bay is laid bare by the lowering of the water level which occurs from time to time during strong northerly winds which push water out of Aransas Pass.

The continental shelf outside St. Joseph and Matagorda islands is notable for the regularity of its contours. As shown in Figure 2, the contours conform in general with the concave shape of the coastline. Near the shore there is a relatively steep zone (0.67 per cent) extending to 20-foot depths, beyond which the gentlest

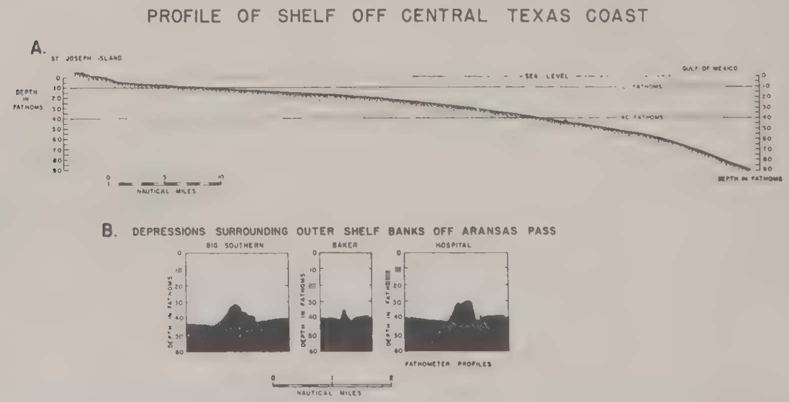

FIG. 5A.—Echo-sounding profile of shelf seaward of St. Joseph Island. Inner part from U. S. Coast and Geodetic Survey data. 5B.—Echo-sounding profile across three banks on outer shelf, showing ring depressions and small benches.

slopes of the shelf are found out to about 100 feet. Seaward from the 100-foot contour the slope increases gradually, having an average grade of 0.16 per cent to to the edge of the shelf, which occurs at about 360 feet (60 fathoms) off Aransas Pass, but is nearer 270 feet on the northeast off Matagorda Bay. The nature of this slope is shown on the chart (Fig. 2) and from a profile taken from one of the fathograms made during offshore collections (Fig. 5; also Fig. 17).

The chief irregularity of the shelf is found in the group of banks which rise from 30 to 60 feet above a mean depth of 250 feet off Aransas Pass. Traverses of these banks with a fathometer have shown that most of them are surrounded by broad, ring-like depressions generally having a depth of about 6 feet (Fig. 5b). The tops of these banks are relatively flat and there are flat steps or terraces on the sides. It is difficult to say from available information whether these terraces occur at the same depth on the different banks although there is a slight indication that this may be the case.

GEOLOGY AND PHYSIOGRAPHY OF LAND AREA

For the Quaternary geology of the area the writers are dependent on the information provided by M. N. Bramlette, along with well data from engineering reports. Some data have also been provided by R. J. LeBlanc, Hugh Bernard, and W. Armstrong Price (1933).

The generalized compilation, shown in Figure 6, indicates two topographic trends. One of them runs northeast and southwest and is represented by the present-day barrier islands and by an old Pleistocene barrier called Live Oak Ridge, which extends through Aransas Pass and Rockport and northeastward except where it is interrupted by the bays. This ridge, which rises to heights of 30 feet, is similar in general character to St. Joseph and Matagorda islands which lie along the present outer coast. Northwest of these old barrier islands there are lowlands which represent old bays, some of them still below sea-level, such as Port Bay west of the Rockport area. The other significant trend is from north-northwest to south-southeast and is the result of the valleys which evidently were cut during the glacial stages of lowered sea-level and have been nearly filled with sediment during and following the post-glacial rise in sea-level. The combined Guadalupe and San Antonio rivers are the principal streams entering this area, although there are three small streams coming into Copano Bay. Along these old valleys there are fluvial and delta deposits. The Guadalupe River has built a delta at least 10 miles out into the head of San Antonio Bay, and Mission River has made a much smaller delta in Mission Bay, a tributary of Copano Bay.

The barrier islands are diversified physiographically. Inside of the long sand beach there are extensive dune tracts (Fig. 7), some extending more than a mile in from the beach. Beyond some of the beaches is a series of long so-called "beach" ridges parallel with the shore in a belt having a width of as much as a mile. The maximum widths of both St. Joseph and Matagorda islands are in part related to great overwash fans (Fig. 8). Some of these low areas are traversed from time to time by storm tides, and elsewhere the bifurcating of the channels is indicative of overwash.

The barrier flats on the northeast end of St. Joseph Island and along most of the bay side of Matagorda Island consist of a mass of more or less circular lakes and irregular channels with less actual land area than that covered by shallow water (Fig. 9). During times of low sea-level in the bays the land area becomes considerably enlarged. A similar swampy area is found along the east side of lower San Antonio Bay and along adjacent parts of Espiritu Santo Bay. The circular lakes are commonly rimmed by slight rises on which there are masses of small bushes. Comparison of airplane photographs made in 1929 with those made recently shows that some of the lakes have expanded so that rims formerly distinct have become intersecting (Fig. 10).

CLIMATE

The climate is of particular interest in the Rockport area because it is intermediate between two belts, one on the northeast called by Thornthwaite (1948)

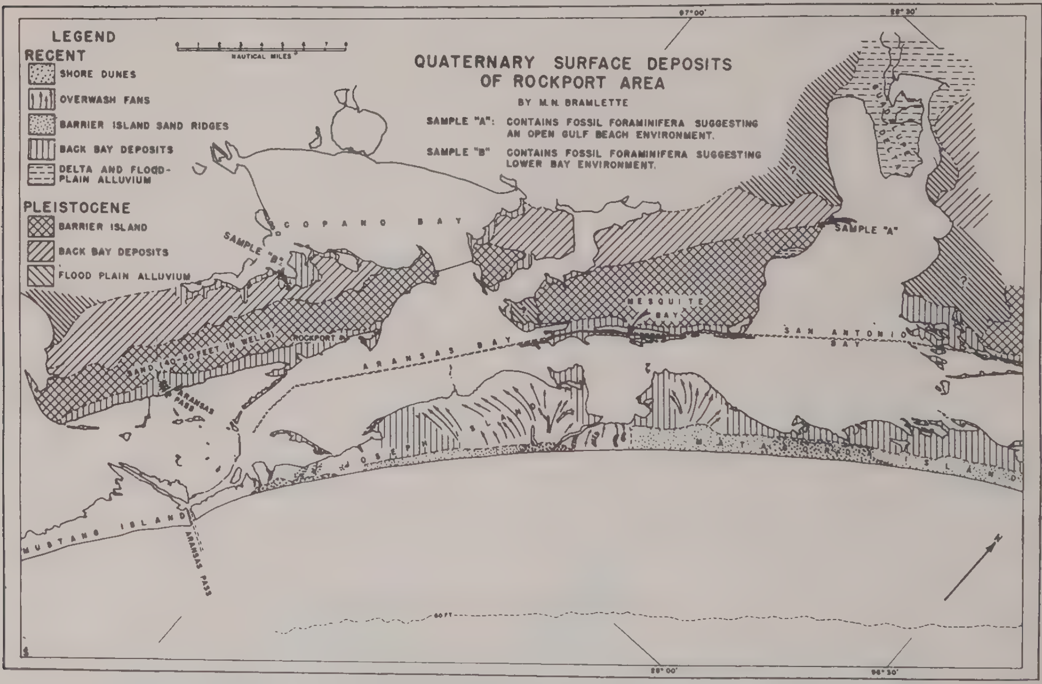
LEGEND
RECENT
SHORE DUNES
OVERWASH FANS
BARRIER ISLAND SAND RIDGES
BACK BAY DEPOSITS
DELTA AND FLOOD-PLAIN ALLUVIUM
PLEISTOCENE
BARRIER ISLAND
BACK BAY DEPOSITS
FLOOD PLAIN ALLUVIUM
NAUTICAL MILES
0 1 2 3 4 5 6 7 8
QUATERNARY SURFACE DEPOSITS OF ROCKPORT AREA
BY M.N. BRAMLETTE
SAMPLE "A": CONTAINS FOSSIL FORAMINIFERA SUGGESTING AN OPEN GULF BEACH ENVIRONMENT.
SAMPLE "B" CONTAINS FOSSIL FORAMINIFERA SUGGESTING LOWER BAY ENVIRONMENT.
97°00'
28°30'
COPANO BAY
SAMPLE "B"
SAMPLE "A"
SAND (40-80 FEET IN WELLS)
ROCKPORT
ARANSAS PASS
ARANSAS BAY
MESQUITE BAY
SAN ANTONIO BAY
ST. JOSEPH ISLAND
MATAGORDA ISLAND
MUSTANG ISLAND
ARANSAS PASS
?
60 FT
N
28°00'
96°30'

Fig. 6.—Compilation by M. N. Bramlette, showing Quaternary deposits of Rockport area. Arrows indicate general direction of channels in overwash fans.

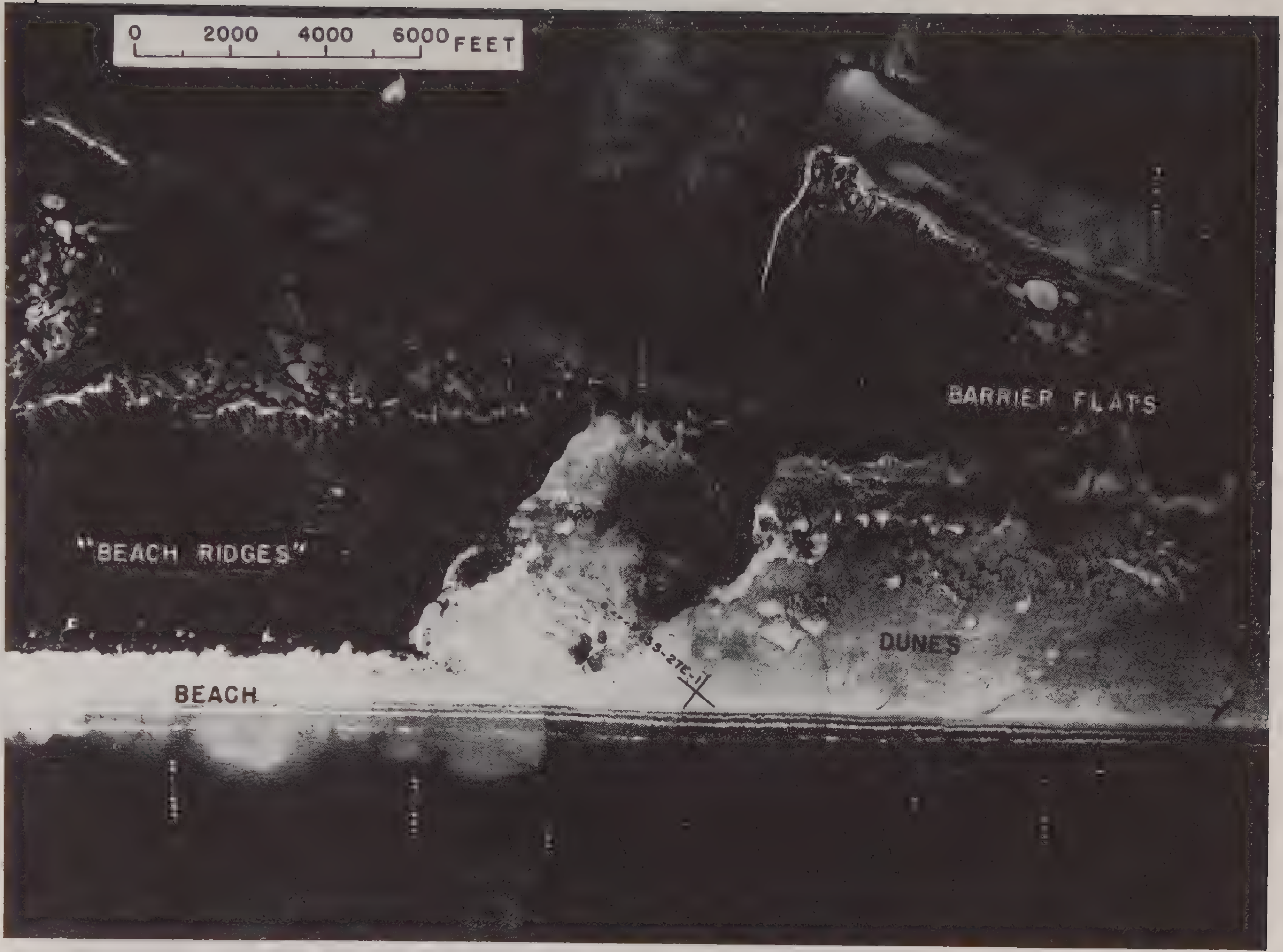
0 2000 4000 6000 FEET
BARRIER FLATS
"BEACH RIDGES"
DUNES
BEACH
3-27E-1

FIG. 7.—Aerial photograph of Matagorda Island, showing three environments of barrier islands. Small rip currents shown by cloudy water along shore. Shallow bars indicated by breakers in foreground and by lines parallel with coast in upper left. Aerial mosaic by courtesy of Edgar Tobin Surveys.

"moist sub-humid," and the other on the southwest "dry sub-humid" changing in a short distance to "semi-arid." As a result of the drought which has affected most of Texas during the last 6 years, the climate of the Rockport area has become semi-arid. The rainfall at Victoria in the San Antonio River basin since 1948 has averaged 30 inches per year as compared with a previous average rainfall of about 39 inches for the years 1935–1947.

The temperature of the Rockport area ranges from about 100° in summer to about 32° in winter. In summer the temperatures are fairly constant around 85°, being considerably ameliorated during the day by the southeast winds along the the coast which blow in from the Gulf, where the water averages about 84°. In

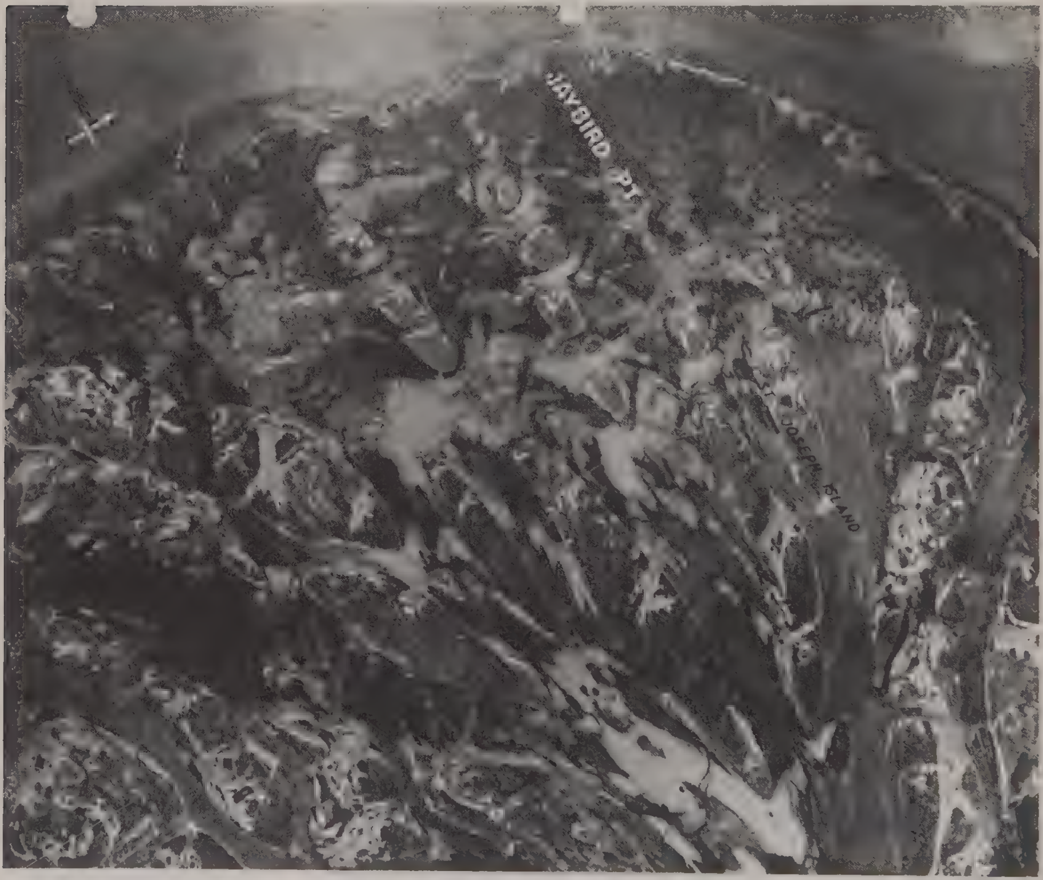

FIG. 8.—Branching overwash on St. Joseph Island in vicinity of Jay Bird Point. Aerial mosaic by courtesy of Edgar Tobin Surveys.

winter the temperature shows tremendous alternations. From a normal 60° it is frequently lowered to 40° or 50° by strong northers. These occasionally reduce the Rockport temperature to freezing or below freezing. The most severe northers may lower the temperature to such an extent that the fish are killed in large numbers (Gunter and Hildebrand, 1951).

Almost every year one or more hurricanes traverse the Gulf coast. These have crossed the Rockport area on three occasions since the Weather Bureau started keeping records (1919, 1941, and 1945). In each case extensive damage was done to one or more of the towns in the area, and undoubtedly the sedimentation in the bays was influenced. Even when hurricanes pass at some distance from the area, the effect is observed because the Gulf water level rises, causing the flooding of the outer beaches. Water moves rapidly up through the inlets and thus tends to flood the bay shores. Twice during the project field investigations, distant hurricanes produced this flooding (Fig. 11).

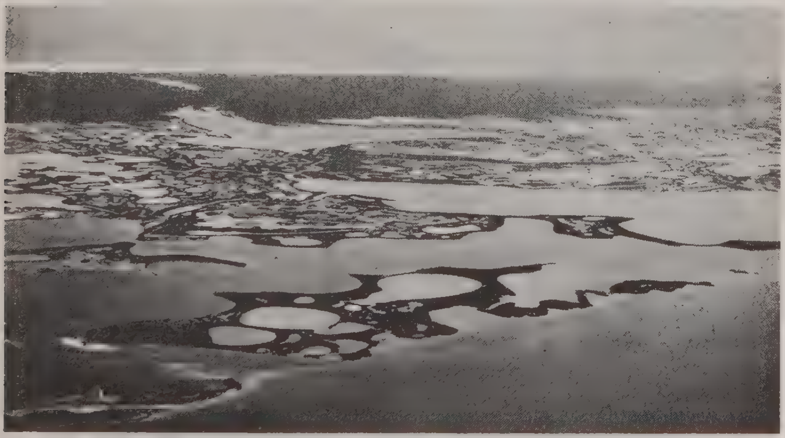

FIG. 9.—Lakes and channels of marshy zone on bay side of Matagorda Island.

Long period variations in rainfall have a strong effect on the water of the bays. During a dry period when the principal rivers are low, evaporation exceeds run-off causing a great increase in salinity. Under these conditions the lower bays develop a salinity slightly higher than that of the open ocean. After the occasional floods the salinity is decreased very rapidly, especially near the river mouths, although the low salinity persists only for a relatively short time.

METHODS OF COLLECTION AND STUDY

FIELD PERIODS

Seven field periods have been spent in the Rockport area and these have lasted from 10 days to 3 months. The initial field work was conducted during the entire summer of 1951. Other periods, all of shorter duration, have covered a part of each of the other three seasons.

During the field work the greater part of the time has been spent in collecting samples from the many environments of the bays. Several cruises have been made in the open Gulf, and on two occasions these have included sampling across the entire width of the continental shelf. Briefer trips have extended out only to

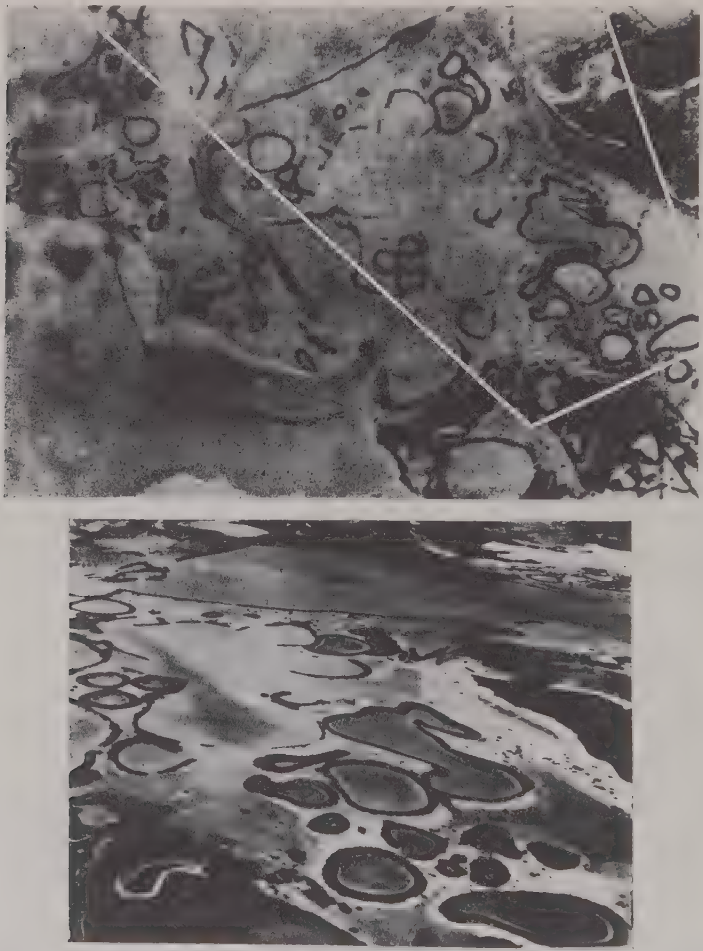

FIG. 10.—Comparison of circular lakes and photographs made in 1929 (upper) and 1951 (lower). Lake rims have intersected in several places. Upper is aerial mosaic by courtesy of Edgar Tobin Surveys.

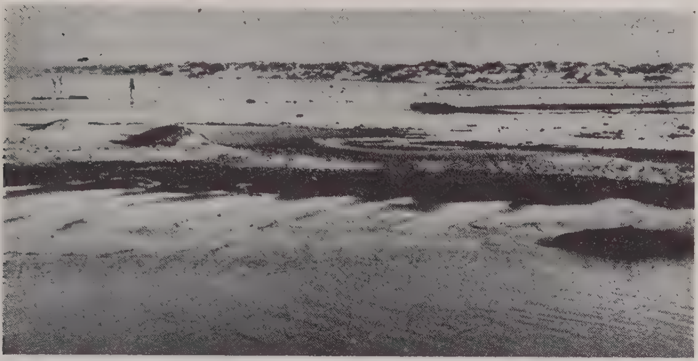

FIG. 11.—Flooded beach at north end of Padre Island, during hurricane of September 26, 1953, which hit Gulf coast east of Mississippi Delta, 450 miles from position of photograph. These beaches are flooded only during hurricane tides so far as known.

the 10-fathom curve. The open Gulf work has ranged somewhat beyond the general bounds of the Rockport area, as can be seen from the sample localities in Figures 1 and 2. The barrier islands were visited on many occasions during which collections were made in their various environments.

EQUIPMENT

Boats used in the work have varied from the 110-foot *Alaska*, belonging to the U. S. Fish and Wildlife Service and used in offshore collections, down to small motorboats for work in the bays.

The sampling equipment has been varied. Some heavy gear has been used in the offshore work, such as piston samplers which obtained cores up to 15 feet in length, and a Van Veen sampler which collected 2 cubic feet of material (Fig. 12). The piston samplers (Silverman and Whaley, 1952) are modifications of those developed by Kullenberg (1947) for the Swedish Deep Sea Expedition. The cores collected are not as long as those obtained by Kullenberg partly because of of the shoaler water where hydrostatic pressure is less effective and partly because the vessels which have been used were not equipped to handle the heavy weights necessary for long cores. The Van Veen sampler, in addition to collecting a large amount of material, obtains an essentially undisturbed sample in fine sediments which is useful in determining the nature of minor sedimentary structures.

Many of the samples were taken by a short coring device known as a Phleger Bottom Sampler (Phleger, 1951, Pl. 2). Other larger-diameter corers of similar principle have also been employed. All of these coring devices have core liners which can be removed from the barrel in order to keep the sample intact. In many cases the cores have been frozen in dry ice to preserve them for special work on bacteriology and chemistry in the laboratory. An orange-peel sampler which holds about 0.3 cubic foot of material and a NEL sampler (LaFond and Dietz, 1948) have been used to obtain many samples in sandy bottoms as well as samples for biological purposes. Because of the shallow water in the bays, most cores were obtained by a very simple device, which consists of a metal container into which long tubes of plastic are inserted. This is pushed into the bottom from the deck of the boat.

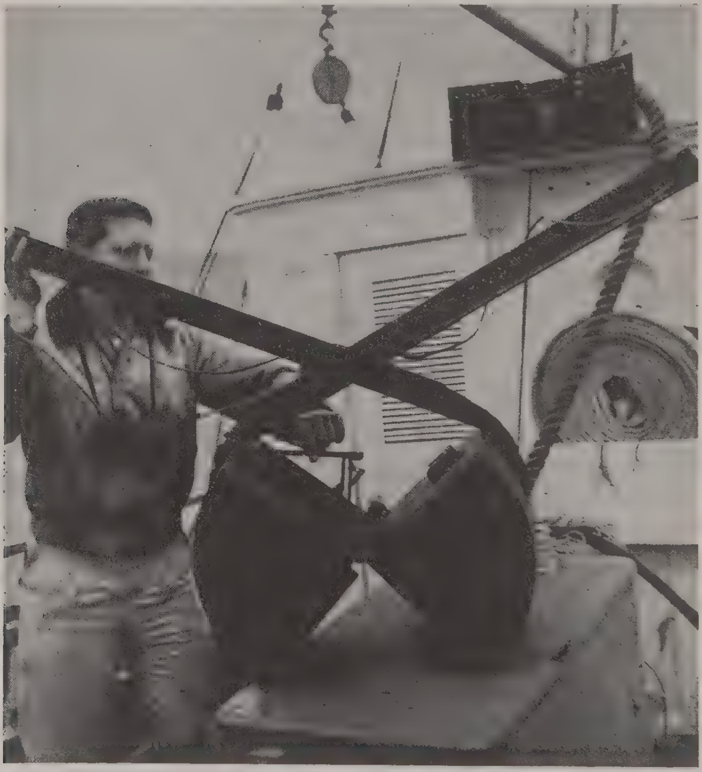

FIG. 12.—Van Veen sampler in semi-open position. Shows release which drops when sampler hits bottom, allowing it to come up in closed position.

Measurements of pH and Eh have been made in the field in order to determine hydrogen ion concentration and the oxidation-reduction potential of freshly collected samples. In addition, water samples have been collected and many water temperatures measured.

In order to obtain closely spaced cores, a "Bident" corer was used which consists of two core barrels mounted on the same frame. They are separated by 33 inches making it possible to determine the continuity of any layering. During much of the work three cores were taken at each station, giving an opportunity for a comparison of closely spaced cores.

FIELD STUDIES

The early work consisted of taking a grid of samples over most of the Rockport bays in order to outline the various sedimentary environments. Most of these samples were taken in core tubes and were retained for analysis. In the work that followed, a series of closely spaced cores was obtained particularly at boundaries between sediment units. Some of these cores were removed from the liners in the field, described immediately, and then discarded. This method was used for one closely spaced sample traverse across San Antonio Bay and in several traverses out from the shore in Aransas and Mesquite bays. Because further study of many samples was desirable, this discarding of cores was soon abandoned.

During most of the field work extensive observations were made of environmental factors such as water temperature, currents, turbidity of the water, wind, and general weather conditions at the time of collection.

LABORATORY STUDIES AND TECHNIQUES

PARTICLE-SIZE ANALYSES

Most of the samples collected in the field work have been analyzed for particle-size distribution. All but the dune sands were disaggregated by using a 0.025 normal solution of sodium hexametaphosphate in which the samples were soaked 2–24 hours according to the clay content. This method breaks up all but the firmly cemented aggregates. Following the disaggregation, the sediments are washed through a sieve which retains all particles greater than $\frac{1}{16}$ mm. (4 phi). This coarse fraction is subject to settling-tube analysis in the method developed by Emery (1938) and later modified by Poole, Butcher, and Fisher (1951), or is dried for sieving if the material is to be fractionated and studied under the microscope.

A working method for the rapid size analysis of the sediments finer than $\frac{1}{16}$ mm. was needed. The hydrometer method was selected because it is faster than the pipette method and is comparable in accuracy. An objection to hydrometer size analysis has been that when the hydrometer is placed in a settling suspension after a known time interval, the density measured can not be correlated with any exact level in the suspension and, therefore, can not be related to a definite settling velocity. However, this objection was overcome by Day (1950) who developed a theoretical method of determining the depth in the suspension (called the "effective depth") where the density is equal to that shown on the hydrometer.

A practical method was needed for applying Day's equation for finding the effective depth at any time interval and, hence, the settling velocity at that depth in the suspended sediment being analyzed. A graphical solution to the equation was developed by D. L. Inman and J. D. Frautschy and from the effective depths and settling times the settling velocities can be determined. The final step was the construction of a nomograph relating settling velocities to diameters. This entire method was simplified by using a known hydrometer, and soil cylinders that had a standard inside diameter so that tables relating hydrometer readings to effective depth could be made, thus eliminating calculations for effective depth for each analysis.

BACTERIOLOGY

The studies carried on by D. E. Contois under the direction of Claude E. ZoBell have used methods indicated briefly as follows. The relative abundances of certain specific bacterial groups in sediment samples are determined by standard plate counts. These are physiological groups consisting of

(a) aerobic saccharolytic bacteria,
(b) aerobic proteolytic bacteria, and
(c) aerobic lipolytic bacteria,

and environmental groups consisting of

(d) aerobic marine bacteria,
(e) aerobic terrestrial bacteria, and
(f) anaerobic marine bacteria.

To ascertain the relative abundance or activity of any specific group, the number of bacteria of that group in a sediment sample is divided by the number of aerobic marine bacteria. For example, the number of aerobic terrestrial bacteria is divided by the number of aerobic marine bacteria to measure relative terrestrial influence. To measure relative proteolytic activity, the number of protein hydrolyzers is also divided by the number of aerobic marine bacteria. Thus in effect, the abundances of the various groups listed are expressed in terms of the number of common aerobic marine bacteria in the sample. The resulting ratios are coded by taking the logarithm of 1,000 times the ratio—i.e., $X' = \log(1{,}000 x X)$. This better assures a normal distribution of the variables and allows the application of statistical tests of significance.

Analyses of initial data indicate that the distributions of these groups exhibit statistically significant differences between samples from various localities in the Rockport area and at times between samples from different depths within a locality. Also, determinations of total populations of aerobic marine bacteria in selected samples indicate viable populations of these organisms of from 11.5–14.5×10^4 bacteria per gram of oven-dried sample. Some of these samples were collected from depths within the sediments as great as $28\frac{1}{2}$ feet. Thus these groups are regarded as an excellent means of characterizing sedimentary environments and processes as well as being agents of diagenetic processes.

TANK EXPERIMENT ON ORGANISMS

Laboratory experiments were conducted, involving the effects of burrowing organisms on the sediments in which they live. Collections were made in the San

Diego area of burrowing organisms as nearly similar to those of the Rockport area as possible. These were placed in specially constructed aquaria containing sediment of varying textures and combinations of layering. The results of these

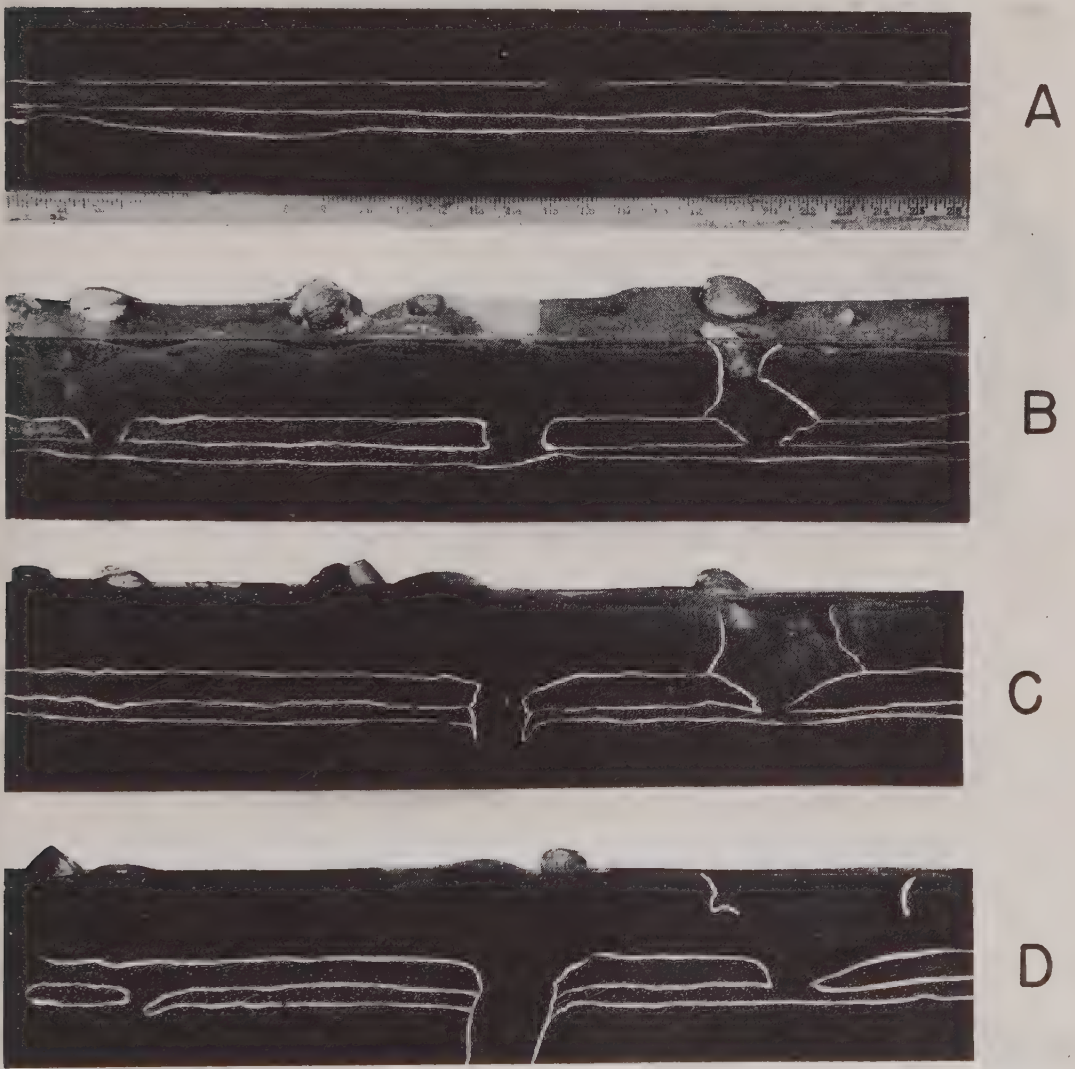

Fig. 13.—Tank experiments showing progressive effect of burrowing organisms on layered sediments. Photo shows depressions and the cutting-through of layers; also lenses of sand built on surface.

experiments were gratifying in that they showed the destructive effects of the organisms on stratification. Figure 13 shows one of the tanks at successive time periods and the destruction of the layers where the organisms were active. It is notable that while destroying stratification of one kind, the animals (particularly the burrowing razor clams *Tagelus*) created other minor sedimentary structures by making mounds of coarser material about their burrows. When buried these would appear as small lenses.

CHEMICAL ANALYSIS

In order to facilitate the efficient chemical analysis of sediments and their interstitial and overlying waters, several new analytical procedures were developed and other standard techniques of processing the samples were improved by George Bien of Scripps Institution. The extraction of interstitial water from cores was made more efficient by the utilization of a sintered steel filter in a newly designed press. This device takes about $\frac{1}{2}$ cubic inch of sample, and from this about $\frac{1}{2}$–$2\frac{1}{2}$ milliliters of solution in equilibrium with the sediment can be squeezed. The exact amount depends on the grain size and water content of the sample.

A high-frequency titration procedure was developed for the determination of the sulphate and chloride contents of very small samples of water. The method was adopted for the analysis of interstitial water obtained in the press device described previously. Details of this technique can be found in a paper by Bien (1954).

The carbonate analyses were made by a standard procedure which was adapted for the recent sediment samples. Carbonate was determined manometrically by measuring the carbon dioxide evolved as a gas when the sample was digested in normal sulphuric acid. The volume of gas is corrected to standard temperature and pressure and then converted to carbonate as calcium carbonate by the formula,

$$0.1605\ VP/TW = \%\ \text{calcium carbonate},$$

where V is observed volume, P is pressure corrected for water vapor pressure at the room temperature, T is the room temperature in degrees Kelvin, and W is the weight of the sample used. The number 0.1605 is a conversion factor. This method is rapid and accurate. It is far more satisfactory than the dilute HCl treatment which removes more than the carbonates from the sample.

Standard analytical methods which were used in the analysis of the sediments and their interstitial and overlying waters are as follows.

1. The Kjeldahl method was used for the determination of total nitrogen in the sediments. The only modification made was: the ammonia was absorbed in standard potassium bi-iodate solution and the excess acid back titrated with sodium hydroxide solution which was standardized with the same standard $KH(IO_3)_2$ solution.
2. Krogh's method, with minor modifications, was used for the determinations of organic carbon in the sediment.
3. The chlorinity of overlying waters was determined by the regular Mohr method with Knudson burets.
4. Potassium and sodium of the overlying waters were determined with the flame photometer.

GENERAL LITHOLOGY OF RECENT SEDIMENT UNITS

Description of sediment units and their general lithologies is important for two reasons. First, it is the only way to give an over-all picture of the sedimentary framework of the area. Second, it serves to illustrate that sediment units based only on textural terminology are usually insufficient to define environments of deposition. The general framework to be presented has a textural nomenclature developed by API Project 51 after systems in existence were found to be lacking in certain respects (Shepard, 1954). The system is based entirely on proportions of sand, silt, and clay as represented on a triangle[5] (Fig. 14).

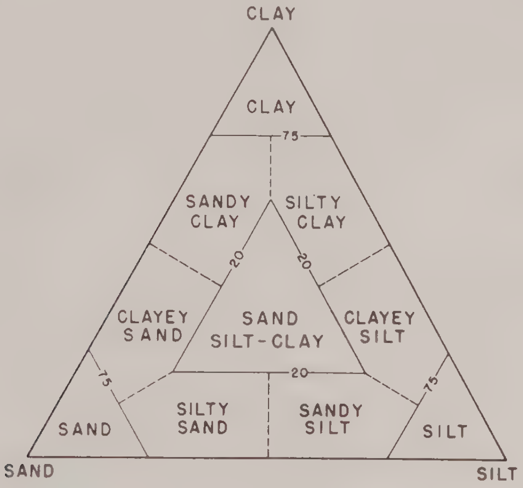

FIG. 14.—Nomenclature based on sand-silt-clay percentages.

BAY SEDIMENTS

Figure 15 shows the distribution of bay sediment units. The sediments tend to have an orderly arrangement, consisting of silty clays in the deep central parts, a gradational mixed zone of sandy clay, clayey sand, or sand-silt-clay, and a generally narrow zone of fringing sands in the shallowest areas where active stirring by waves takes place. This ideal arrangement is complicated, however, by variations in source, topography, and water circulation so that exceptions to the order are common. The most prominent areas which do not conform with the general arrangement are northeast and southwest Aransas Bay, southeast San Antonio Bay, and Mesquite Bay. These broad areas of clayey sand and sand-silt-clay are the result of abundant sand supply and considerable mixing. The mixing is apparently the result of stronger current action in the narrows such as those at the juncture of Espiritu Santo and lower San Antonio bays, and in the narrow connection between Mesquite and Aransas bays. Mesquite Bay is also further affected by a small pass into the open Gulf which introduces sand from the barrier islands or from the Gulf. The clayey sand areas in lower Aransas Bay and behind Mud Island are also near an inlet to the open Gulf. The northern end of San Antonio Bay which is split by the Guadalupe River Delta lacks both the zone of fringing sands and the mixed sediments. This omission of apparently normal sediment units is evidently the result of the small sand supply introduced by the Guadalupe River and the inaccessibility of the sands of the old and new barrier islands on the south.

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[5] This new system represents a compromise which was found to be acceptable to a large number of American sedimentationists who were consulted.

In addition to the sediment units formed predominantly of mineral detritus, the bays have irregular areas of shell reefs and reef detritus. These are largest and most common in San Antonio and Copano bays, but occur to some extent in all the bays studied.

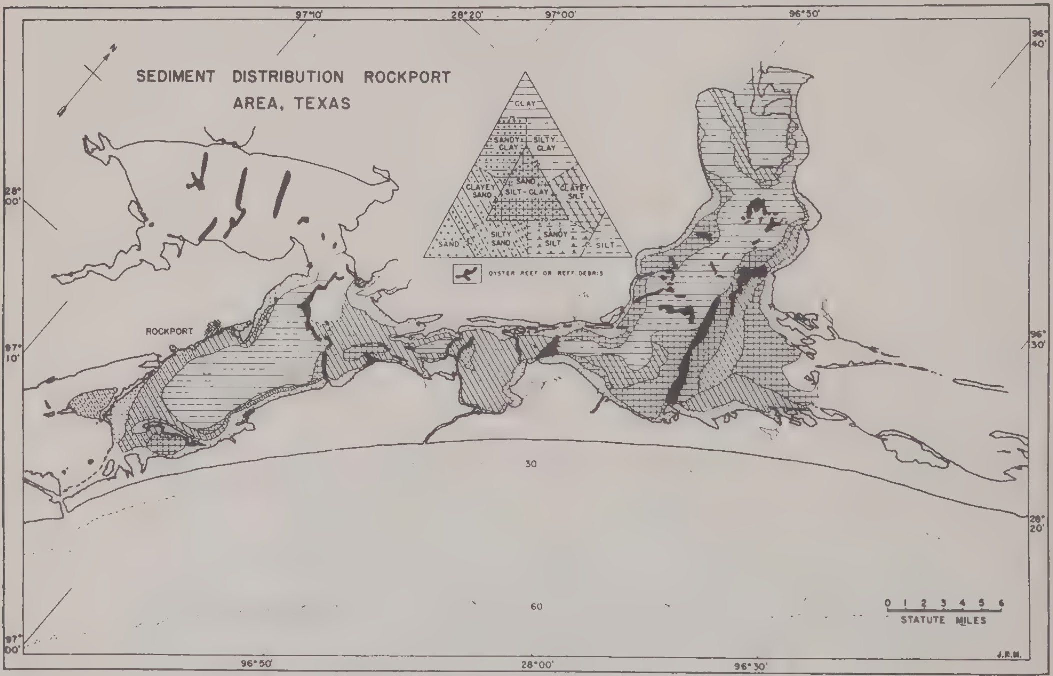
97°10'
28°20'
97°00'
96°50'
96° 40'
N
SEDIMENT DISTRIBUTION ROCKPORT AREA, TEXAS
CLAY
SANDY CLAY
SILTY CLAY
CLAYEY SAND
SAND SILT-CLAY
CLAYEY SILT
20
SAND
SILTY SAND
SANDY SILT
SILT
OYSTER REEF OR REEF DEBRIS
28° 00'
ROCKPORT
97° 10'
96° 30'
30
28° 20'
60
0 1 2 3 4 5 6
STATUTE MILES
97° 00'
J.R.M.
96°50'
28°00'
96°30'

Fig. 15.—Sediment distribution in Rockport area bays based on sand-silt-clay content.

BARRIER ISLAND SEDIMENTS

The barrier island sediments consist predominantly of sand with little else on the Gulf side. These sands occur as a wide beach along the outside of the islands and as dunes which spread rather widely across the islands in a band in general parallel with the Gulf shores. Both the beaches and the dunes have clean, well sorted sand, as commonly observed in other areas. The so-called "beach" ridges which are found inside the first line of dunes along parts of St. Joseph and Matagorda islands have the same well sorted sand as the beaches and dunes. As explained later, the constituents and the roundness of the sands from these ridges are much more like dune sands than beach sands. This is despite the topographic contrast between the ridges and the active dunes of the area (Fig. 7).

The low parts of the barrier islands inside the dunes and "beach" ridges are variable in texture but are predominantly sand with appreciable amounts of silt and clay in most samples. On St. Joseph Island these flat areas consist largely of overwash fans and commonly have 80 per cent or more of sand. On Matagorda Island, where overwash fans are less extensive, there is more silt and clay. This is particularly true of the bay fringes in the channel and swamp area which borders San Antonio and Espiritu Santo bays (Fig. 7). In a few of these areas the sediments have a high percentage of clay, but this is rare and most of the "mud" flats and channels have sediment consisting of at least 50 per cent sand. Inlets which connect the open Gulf and the bays are also predominantly sand with varying but small amounts of silt and clay.

CONTINENTAL SHELF SEDIMENTS

The shelf sediments show more variation in texture than do the barrier island sediments (Figs. 16 and 17). This is also indicated by some samples obtained in the same area by Stetson (1953). Along the island shores in the shallow open Gulf, the sediments are predominantly sand. These shallow sands extend seaward to approximately the 30-foot contour. Seaward of this sand zone the sediments change abruptly to a sand-silt-clay with only a narrow band of silty sand intervening. At the south off Corpus Christi Bay the sand-silt-clay band is very narrow but it widens continuously northward until it comprises almost the entire shelf off the Colorado and Brazos rivers. In the southern section either a silty clay or a clayey silt lies seaward of the narrow band of sand-silt-clay. Off St. Joseph and Matagorda islands the shelf is covered with fine sediment, very largely a silty clay. For the most part, the sand content decreases seaward and the clay increases. The sand content is very small on the outer shelf in this southern area, but north of Pass Cavallo, the outer shelf runs high in sand, much of it 50 per cent or more.

A high content of silt is a feature which seems to be common to almost the entire continental shelf, except very near the shore. Outside the 5-fathom curve there are very few samples where the silt is less than 30 per cent, the chief exception being found in the sample line off the Brazos River where the silt content

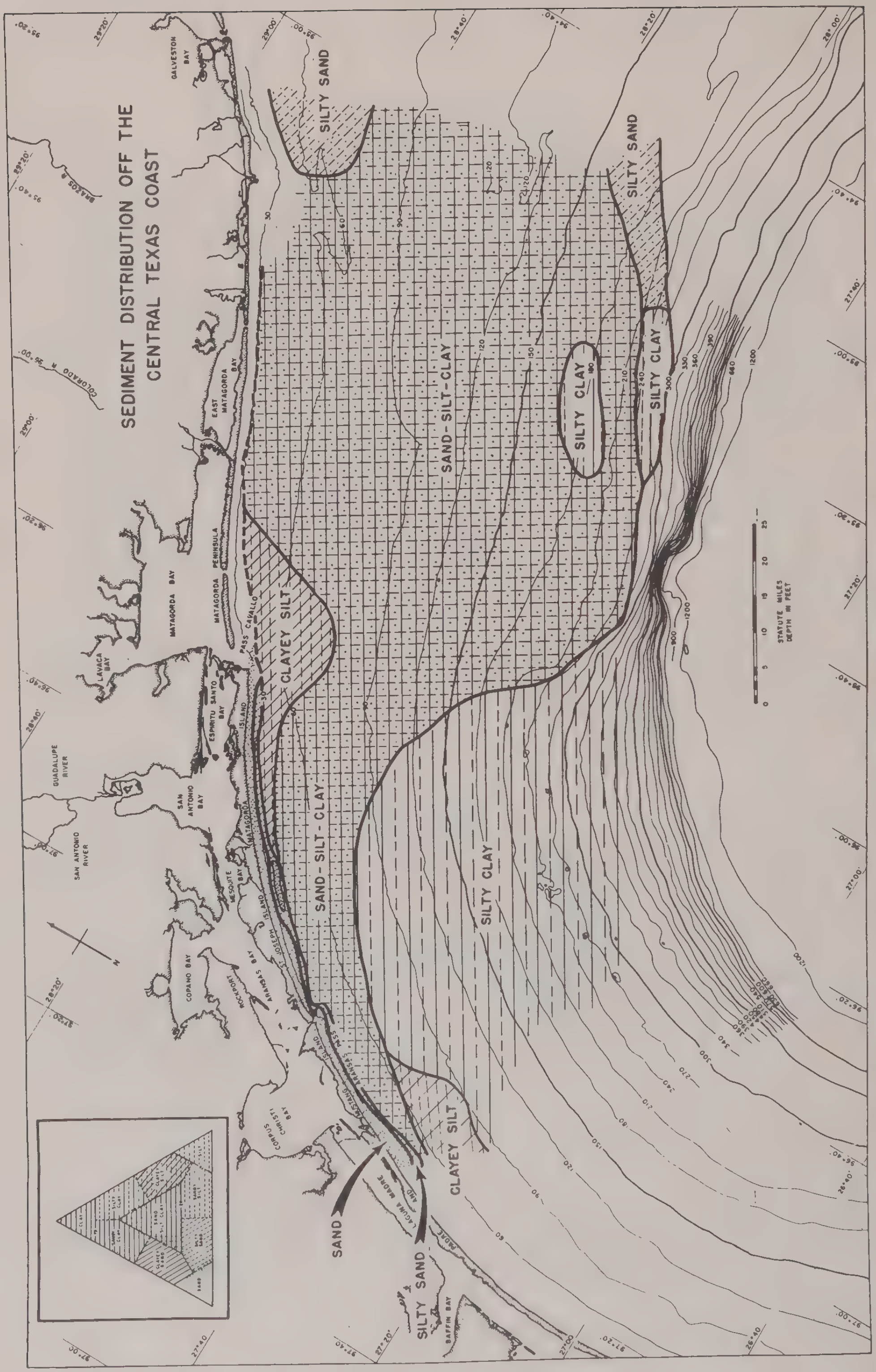
SEDIMENT DISTRIBUTION OFF THE CENTRAL TEXAS COAST
SAND-SILT-CLAY
SILTY CLAY
CLAYEY SILT
SILTY SAND
SAND
GALVESTON BAY
BRAZOS R.
COLORADO R.
EAST MATAGORDA BAY
MATAGORDA BAY
MATAGORDA PENINSULA
PASS CAVALLO
LAVACA BAY
ESPIRITU SANTO BAY
MATAGORDA ISLAND
SAN ANTONIO BAY
GUADALUPE RIVER
SAN ANTONIO RIVER
MESQUITE BAY
ST. JOSEPH ISLAND
ARANSAS BAY
ROCKPORT
COPANO BAY
CORPUS CHRISTI BAY
ARANSAS PASS
MUSTANG ISLAND
LAGUNA MADRE
PADRE ISLAND
BAFFIN BAY
N
STATUTE MILES
DEPTH IN FEET
0
5
10
15
20
25
30
60
90
120
150
180
210
240
270
300
330
340
360
390
640
900
1200
29°20'
29°00'
28°40'
28°20'
28°00'
27°40'
27°20'
27°00'
26°40'
97°20'
97°00'
96°40'
96°20'
96°00'
95°40'
95°20'
95°00'
94°40'
CLAY
SAND
SILT
CLAYEY SAND
SANDY CLAY
SILTY CLAY
CLAYEY SILT
SAND-SILT-CLAY
SILTY SAND
SANDY SILT

FIG. 16.—Generalized sediment distribution on continental shelf off central Texas coast based on sand-silt-clay content.

varies around 20 per cent (Fig. 17). The addition of the sand to the sediment in the northeast may be in some way connected with the Brazos and Colorado rivers which enter the coast here. At the mouths of both these rivers the sediments are much more sandy than those at the mouth of the Guadalupe.

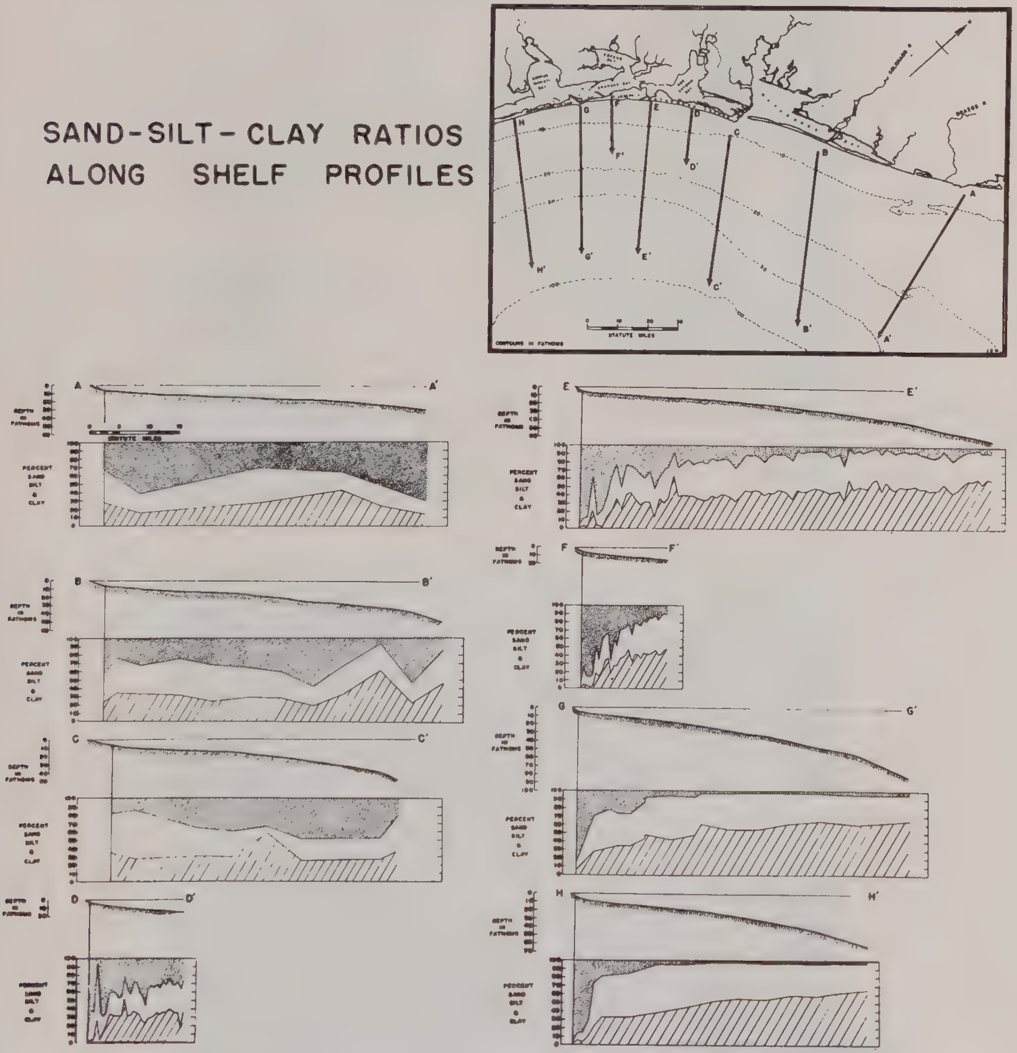

FIG. 17.—Variation in sand-silt-clay in series of lines extending out across continental shelf in central Texas coast area (see also Fig. 2).

FACTORS INFLUENCING THE ENVIRONMENTS

SEDIMENTARY ENVIRONMENT DEFINED

Since much of the present report concerns "sedimentary environments," it seems advisable to define the term as it is used here. A sedimentary environment is *a spatial unit in which external physical, chemical, and biological conditions and influences affecting the development of a sediment are sufficiently constant to form a characteristic deposit.* The influences include depth of water, degree of protection from wave attack, salinity and temperature of the water (as they influence the biological activities), availability of streams carrying sediment into the area under discussion, the nature of currents such as are necessary to transport sediment in the area, and any other influence which may affect sedimentation. These factors are discussed as they apply to the Rockport area.

SOURCES OF SEDIMENT

Directly or indirectly the rivers can be considered as the principal source of sediments. The combined drainage of the San Antonio and Guadalupe rivers enters at the head of San Antonio Bay, although some of it has spilled over into Green Lake and thus enters the bay indirectly (Fig. 18). In 1935 a cut was made in the river bank, diverting the major flow from the two channels which enter Guadalupe Bay to a channel coming directly into the southwest side of Mission Lake. The outlet from Green Lake comes into the northeast side of Mission Lake. Hence, active delta building is occurring now at both ends of this small restricted body of water (Fig. 18) and little sediment is carried out of the old channels. The flow into Green Lake may account for the very minor changes which have occurred in Guadalupe Delta since the survey of 1874. The San Antonio-Guadalupe system has a flow of a little less than a million acre-feet per year, and these rivers transport about 775 acre-feet per year of sediment in suspension, as measured at stations about 25 miles above the juncture (Texas, 1952). The other streams which enter directly into the Rockport bays contribute much less sediment.

Indirect sources of sediment come to the offshore area from the Colorado of Texas and the Brazos rivers which enter directly into the Gulf at distances of 40 and 90 miles, respectively, northeast of the Rockport area. Judged from stations at a distance of about 40 miles from their mouths, both rivers transport much larger loads of sediment than does the Guadalupe-San Antonio system; the Colorado carries 29,200 acre-feet per year and the Brazos 21,984 acre-feet. The water discharged through these rivers is respectively about 1,000,000 and 5,500,000 acre-feet per year. The Brazos River has been flowing into the Gulf since the time of the earliest published charts. The Colorado, however, has only recently been given a direct connection with the Gulf as the result of a ditch dug by the Army Engineers across Matagorda Peninsula in 1936. Prior to that time the Colorado probably contributed sediment to the open Gulf through Pass Cavallo, which is a natural inlet at the mouth of Matagorda Bay. In addition to

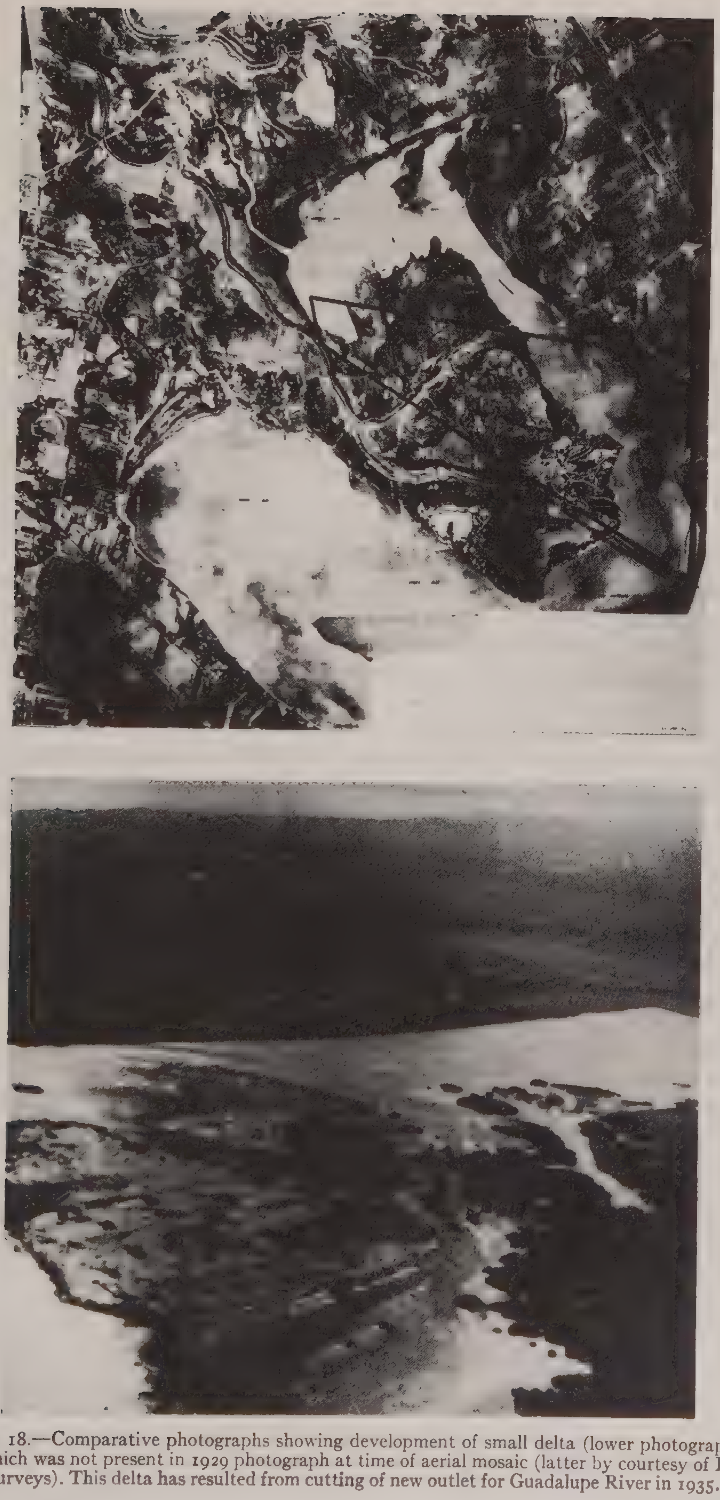

FIG. 18.—Comparative photographs showing development of small delta (lower photograph) in 1951, which was not present in 1929 photograph at time of aerial mosaic (latter by courtesy of Edgar Tobin Surveys). This delta has resulted from cutting of new outlet for Guadalupe River in 1935.

terrigenous minerals, these rivers also introduce significant amounts of wood fragments which are prominent in deposits near the river mouths.

A small source of bay sediment comes from the cliffs situated along the shores of San Antonio Bay and locally in Aransas Bay, along Live Oak Peninsula. No studies have been made of the retreat of these bay cliffs, but similar cliffs were studied in both Galveston and Corpus Christi bays. A retreat of as much as 100 feet in about a century was found in both places. According to W. Armstrong Price (personal communication) a large supply of sediment for the barriers may come from the erosion of cliffs north of Port O'Connor near the outlet of Matagorda Bay. Therefore, it seems likely that the cliffs in the Rockport area form a local source of sediment which may be of some importance.

Biological sources of sediment were particularly important in the bays during the past when the oyster reefs were developing more actively. Intensive oyster raking removes most of the oysters now growing on the reefs but they still form a small source of sediment. The importance of oyster reefs in the past is indicated in the descriptions of the borings which were made along the center of San Antonio Bay (pp. 1555–62); these results are supported by many probings in the various bays (Norris, 1953). Biological sources of sediment are also of some importance in Redfish Bay where an abundance of gastropods and pelecypods are found, and in some bay areas the Foraminifera constitute as much as 2–3 per cent of the sediment. On the outer shelf the Foraminifera are abundant, and locally mollusk shell and echinoid fragments form a significant percentage of the sediment samples.

A small amount of sediment is developed through authigenic processes. In the offshore area, glauconite is found as discrete grains as well as in the tests of Foraminifera, having formed in part as the result of alteration of clays. Pyrite is found rarely in the shelf sediments. In the bays, pyrite forms to a considerable extent in the foraminiferal tests and in other small shells and develops to some extent from an impregnation or replacement of wood fibers. Except in the delta, pyrite is rarely present at the surface in large enough aggregates to be visible in the binocular study of the samples,[6] but it has been found commonly in bay cores at depths more than a few feet below the surface. Glauconite, on the other hand, was observed both near the surface and below in the shelf cores.

Wind-blown dune sand forms a small contribution to the bay deposits and a significant contribution to the barrier flats on the bay sides of the islands. Another small sediment source on the barrier islands comes from evaporation when the sea-level is lowered by changes in wind direction which result in water being blown to the other side of the bay or out of the inlets. Evaporation produces a calcareous evaporite deposit which surrounds the sand grains and thus constitutes a small source of sediment. Salt is deposited also as a result of this evaporation, although this ordinarily does not persist as an important material in the sediments after they become slightly buried. In Redfish Bay the marine grasses constitute an appreciable element in the sediments, but these are of minor consequence in the other parts of the area studied.[7]

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[6] According to M. N. Bramlette, pyrite does occur as minute grains.

DISTRIBUTIVE AGENTS

In the shallow bays, waves produced by moderate to strong winds, which are common in this area, stir the sediment from the bottom so that the water becomes very turbid. Surface currents driven before the wind may be accompanied by a return flow underneath. Where surface eddies develop along the sides of the bays there tends to be a surface return flow. Northerly winds in the winter months are generally strongest and most effective in developing currents. In general, wind-induced currents are more effective in transporting sediments in the bays than are currents coming from the entry of water from the stream mouths. The chief exception to this is found in Mission Lake and Guadalupe Bay, where during times of flood a considerable amount of fresh water enters and moves south towards the upper part of San Antonio Bay. Transportation by residual river flow, combined with currents induced by the northers in San Antonio Bay, evidently carries the bulk of the sediment down the west side of the bay with the result that there may be some counter current coming up the east side with water from Espiritu Santo Bay. The predominant flow down the west side of central San Antonio Bay is in part the result of bottom configuration produced by oyster reefs.

Currents generated by celestial tides are of minor consequence in most parts of the bays although they are significant in and near large inlets like Aransas Pass. Currents in Aransas Pass observed over a period of a year were found to have a greater relation to changing wind conditions than to the tides of the moon and sun. An analysis of wind direction and velocity *versus* direction of current flow is shown in Figure 19. An excellent correlation is evident between northerly winds and outflowing currents, whereas only a fair correlation exists between southerly winds and inflowing currents. This better correlation of current direction with the north winds is as would be expected since longshore and oceanic currents in the open Gulf limit the amount of the hydraulic head built up in the offshore area during southerly winds. The bays, on the other hand, are shallow and relatively restricted so that a strong and continuous northerly wind is capable of piling up a considerable amount of water on the downwind side, leaving the windward bay shores with a tide of one or more feet below normal. The entering rivers further accentuate the outflow through Aransas Pass. During northers strong southerly flows are also observed in the narrows between bays. These are due to concentration of flow at the narrows. A striking inflow through Aransas Pass develops at the time of Gulf hurricanes which cause a general rise of sea-level even at distances of several hundred miles from the storm center. At the times of these sea-level rises old vestigial passes which are ordinarily closed may be opened, carrying water into the bays (Fig. 4).

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[7] Copano Bay has extensive grass flats especially on the west side.

Currents are considerably different in the open Gulf than in the bays. The waves commonly approach the coast diagonally and generate longshore currents (Shepard and Inman, 1951) which are responsible for carrying sediments for great distances along the coast (Bullard, 1942). A local piling-up of water along the shore causes a seaward return flow in the form of rip currents (Shepard *et al.*, 1941) which can be observed frequently from the air (Fig. 7). These currents transport sediment out from the shore and are responsible for carrying the finer sands out from the beaches. Waves, which during exceptional storms break out to depths of at least 30 feet of water, have an important effect on sedimentation. Wave action stirs up the fine sediment from the sea floor and currents transport it both in and out. The part carried shoreward, however, has little chance of deposition under the turbulent conditions near shore so that the net result is offshore transport.

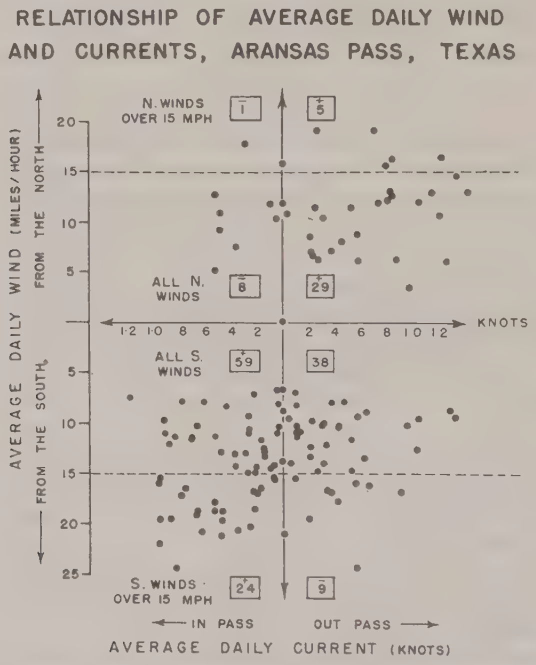

FIG. 19.—Relationship between wind directions and currents in Aransas Pass during year's survey from May, 1952, to April, 1953. Currents measured twice daily at Institute of Marine Science pier, and wind data from U. S. Weather Bureau at Corpus Christi. Top and bottom sections show current velocity and direction for winds over 15 miles an hour. Figures in small squares are totals for each quadrant.

Other currents affecting the area are not as well known as those previously discussed but they are considered briefly. The currents associated with "surf-beat," which is a phenomenon related to the periodic building-up of waves and the development of currents as reflection of this build-up (Munk, 1949), may transport the sediments for considerable distances out from the coast. Sediments carried out either by surf-beat or rip currents may be deposited locally or may be incorporated into the semi-permanent currents which flow predominantly southwest along this coast.

The importance of currents, whatever their cause, is indicated even on the outer part of the shell. Thus the finding of a well sorted sand with Foraminifera suggestive of present conditions in a core from 30 fathoms of water off the Colorado River seems to prove that the currents are strong enough to transport sand. This strong current was confirmed by the difficulty in getting the large Van Veen sampler to the bottom on the outer shelf in the vicinity of the small banks.

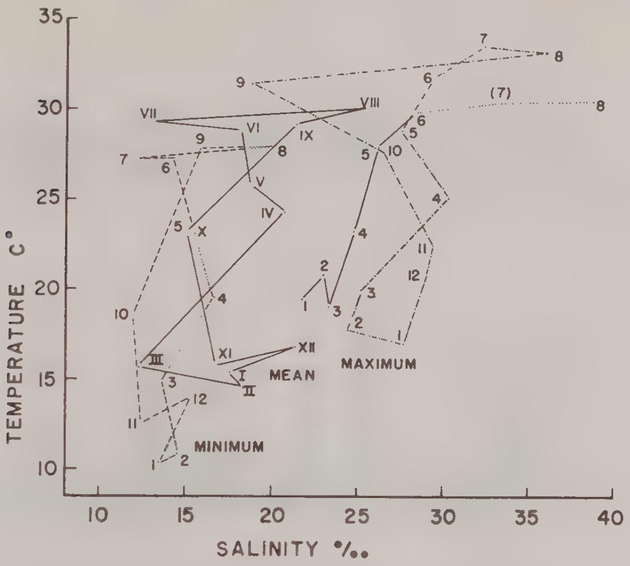

FIG. 20.—Diagram from Hedgpeth (1953, Fig. 23) showing relation of maximum, minimum, and mean averages of temperature and salinity in Aransas Bay. Numbers refer to months of year; Roman numerals refer to the mean.

TEMPERATURE AND SALINITY

Rather extensive information is available on the temperature and salinity of the bays in the Rockport area as a result of the work by Collier and Hedgpeth (1950), Hedgpeth (1953), and a compilation by Parker (1955). These factors are important in sedimentation principally because they control the growth of organisms in the various parts of the bays. A more direct influence comes from the electrolytic effect of the varying degrees of salinity on colloids introduced by the rivers. This problem is not yet solved despite extensive work by petroleum company laboratories and studies such as those of Whitehouse (Whitehouse and Jeffrey, 1953) related to API Project 51.

The bays of the Rockport area are so shallow that the water temperatures change rapidly especially during "northers" when the air is cooled as much as

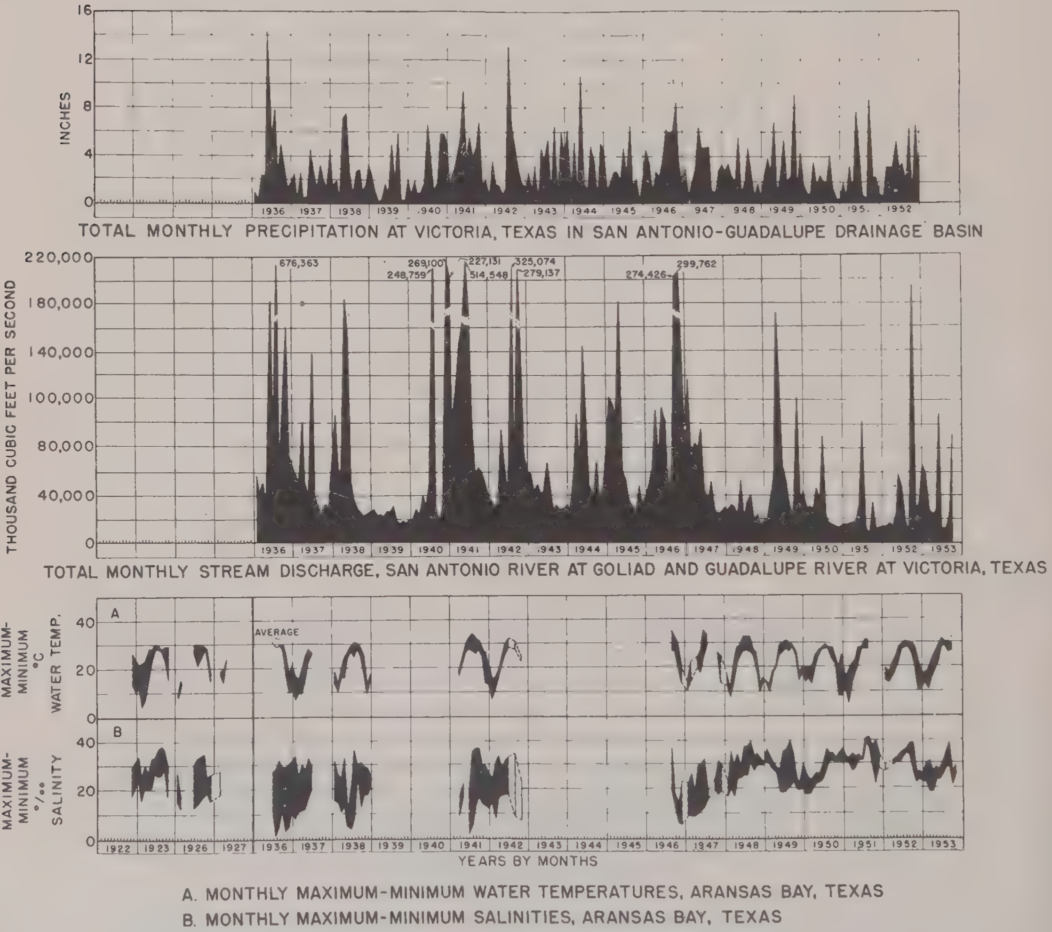

FIG. 21.—Figure from Parker (1955) showing relationships of precipitation in San Antonio-Guadalupe drainage basin and total monthly stream discharge with salinity and water temperature in Aransas Bay.

10°C. in an hour and the wind is strong enough to stir the water to the bottom of the bay. Mean water temperatures for the cold months of January and February lie between 10° and 15°C., and the high water temperatures during July and August are close to 30°C. These temperature extremes are about the same as those encountered in the bays from Laguna Madre to Louisiana (Hedgpeth, 1953, Fig. 23). The water temperature along the open Gulf beach and in Aransas Pass falls as low in winter as it does in the bays but ranges about 2°C. cooler in summer.

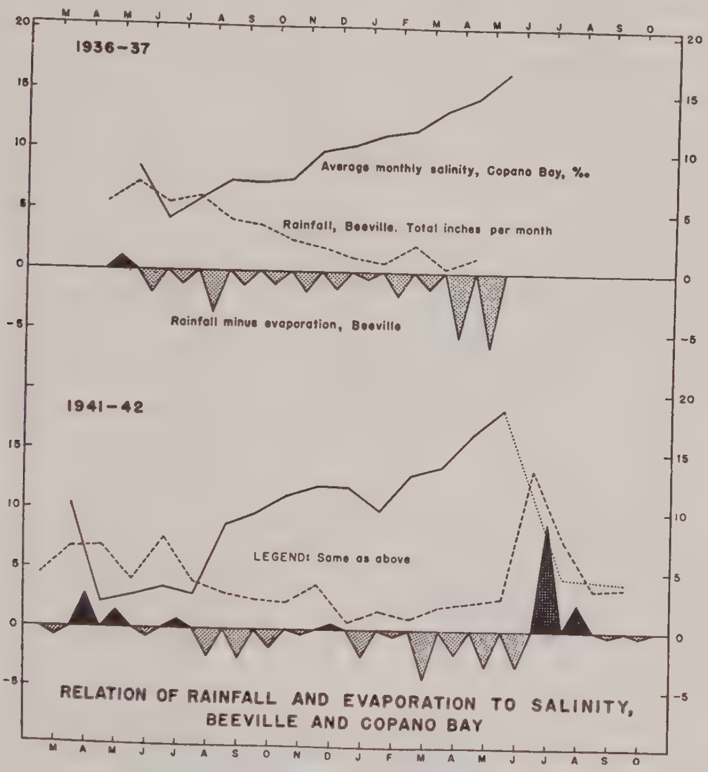

FIG. 22.—From Collier and Hedgpeth (1950, Fig. 20), showing salinity in Copano Bay as related to rainfall in near-by Beeville station and rainfall minus evaporation.

The monthly relation of salinity to temperatures is indicated in Figure 20. It may be seen that salinity does not vary seasonally as much as temperature. For more details of the salinity in recent years the reader is referred to the compilation by Parker (1955). These observations indicate a considerable increase in salinity during the summer with rather sudden drops in May and September.

These drops are the result of the development of flood conditions. Parker shows the average rainfall in the San Antonio-Guadalupe river drainage basin (Fig. 21) as a partial explanation of this variation.

An important factor in the increase of salinity in the bays is the relation of precipitation to evaporation (Fig. 22). Although the rainfall at Beeville (50 miles northwest of Rockport) averages 30 inches, the evaporation is considerably higher, leaving a deficit. As a result the salinity in the lower bays, far from the stream mouths, is often higher in summer than the salinity in the open ocean. This condition becomes very important south of the area in Laguna Madre where the salinity is almost constantly above that of the ocean and reaches 70 $^{0}/_{00}$ in the summer months, compared with the 30–40 $^{0}/_{00}$ typical of the marine environment. Studies in the Rockport area by Ladd (1951) were conducted in 1940 following a period of relatively heavy rainfall which placed the bays in a different salinity range from what has existed since 1948. Thus lower Aransas Bay, which had been called "polyhaline" by Ladd, is now "marine."

During both dry and humid periods salinities are higher on the east side of San Antonio Bay than on the west side. A continuous increase in salinity is found down the west side of the bay and on into Mesquite and Aransas bays. However, in Aransas Bay the recent surveys under dry spring and summer conditions show a maximum in the lower bay which decreases seaward in Lydia Ann Channel, whereas in the older surveys there was a continuous increase from upper Aransas Bay to the open Gulf.

In the bays there is little difference in salinity and temperature from top to bottom, especially during periods of relatively strong wind which produce complete mixing. A real difference often exists in the lower part of Aransas Bay and in the relatively deep waters of Lydia Ann Channel and Aransas Pass. In Aransas Pass during a time of low salinities (1936–1937), Collier and Hedgpeth (1950) found a subsurface intrusion of high-salinity water coming into the channel (Fig. 23). Presumably under present conditions of higher salinity in Aransas Bay this intrusion no longer occurs. Variations in salinity and temperature in relation to several directions of wind and "tide"[8] are indicated in Figure 23. This diagram supports the current measurements (Fig. 19) as it shows that water moves out of the bay with the north wind and into the bay with the southeast wind. Thus the bays in general can be considered as acting as a unit with reference to temperature and salinities.

Salinity and temperature differences between top and bottom in the Rockport bays are very minor compared with those found, for example, at the mouth of the Mississippi River where during low river stages a great salt wedge is intruded under the fresh water which flows out from the river, and where similarly great variations in salinity and temperature are found with depth. Also, the vertical temperature difference is very minor compared with those found in general in the

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[8] Note that "tide" in this case refers to the current rather than to a celestial tide.

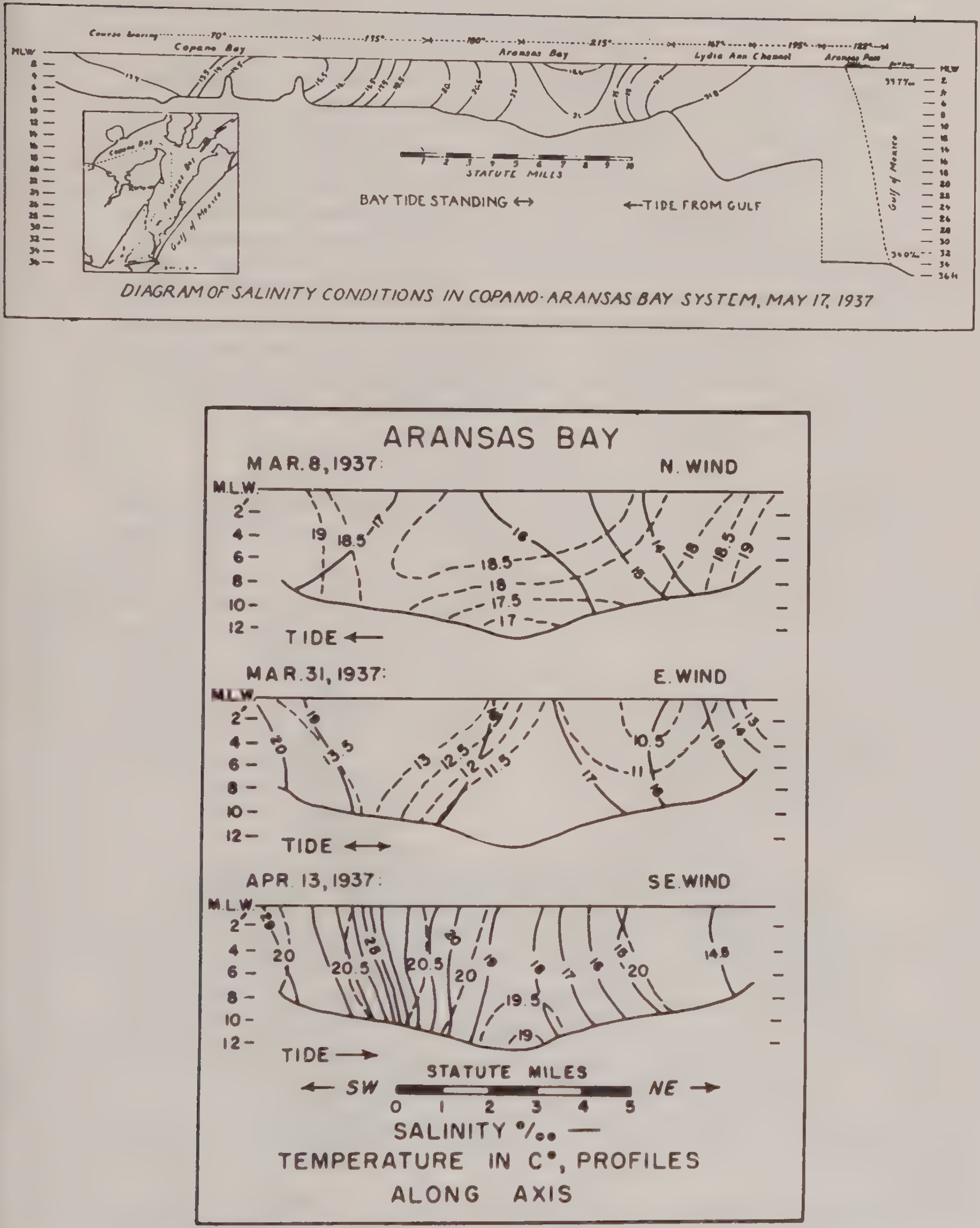

FIG. 23.—After Collier and Hedgpeth (1950, Figs. 15 and 16) redrawn by J. R. Curray, showing intrusion into Aransas Bay of high-salinity water from Gulf, and relation of several directions of wind and current to salinity and temperature in bay.

open ocean where the surface waters become very much heated in summer, and underneath the warm water there is a sharp thermocline to waters of low temperature.

METHODS OF CHARACTERIZING SEDIMENTARY ENVIRONMENTS

In the investigations of API Project 51 the attempt has been made to use nearly all of the standard analysis methods, along with some new methods, of finding differences in sediment characteristics in the various environments of the bays, the barrier islands, and the continental shelf. This work has been aimed at providing stratigraphers more tools for determining the depositional environments of ancient sediments. Methods of studying environment may be considered under: (1) physical characteristics, (2) biological characteristics, (3) chemical, and (4) bacteriological characteristics. Under each of these, many techniques have been used to help define the environment.

PHYSICAL METHODS

Size analysis.—Many methods have been suggested for showing size analyses in graphic form (see especially Krumbein, 1936, and Inman, 1952). Of these

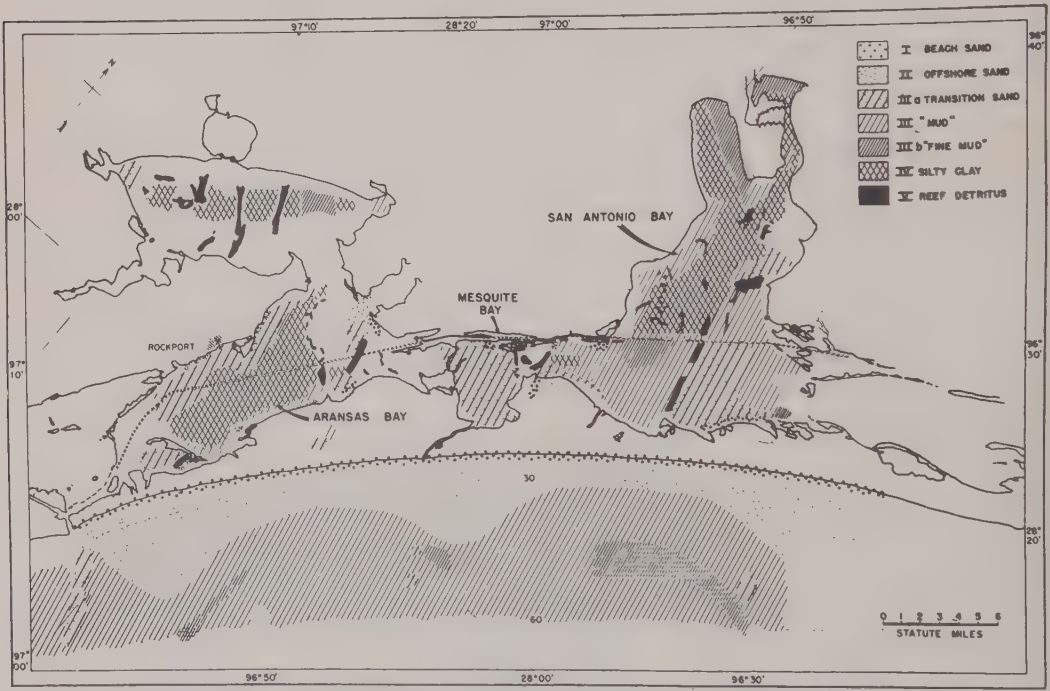
97°10'
28°20'
97°00'
96°50'
96° 40'
I BEACH SAND
II OFFSHORE SAND
IIIa TRANSITION SAND
III "MUD"
IIIb "FINE MUD"
IV SILTY CLAY
V REEF DETRITUS
28° 00'
SAN ANTONIO BAY
MESQUITE BAY
ROCKPORT
97° 10'
96° 30'
ARANSAS BAY
30
28° 20'
60
0 1 2 3 4 5 6
STATUTE MILES
97° 00'
96°50'
28°00'
96°30'

FIG. 24.—From Inman and Chamberlain (1955), showing the distribution of sediment types based principally on three measures of particle size distribution: median diameter, sorting, and skewness.

methods, contours of median diameters, called isopleths, are best known and in some sediment studies this has been the chief method used for sediment description. Isopleths are of importance where the sediments are predominantly well sorted terrigenous materials, but they may be of little value where sediments of distinctly different sizes come from two or more different sources.

A method of depicting sediments, which has the advantage of being based on three measures of particle-size distribution, has been used by Inman and Chamberlain (1955). The sediments are classified according to their median diameter, sorting (deviation), and skewness. These three measures are obtained from the cumulative size frequency distribution of the sediment with the following definitions quoted directly from Inman and Chamberlain:

(1) the phi median diameter $Md_\phi = \phi_{50}$

(2) the phi deviation measure $\sigma_\phi = \frac{1}{2}(\phi_{84} - \phi_{16})$

(3) the phi skewness measure $\alpha_\phi = \dfrac{M_\phi - Md_\phi}{\sigma\phi}$

where $M_\phi = \frac{1}{2}(\phi_{16} + {}_{84})$ is the phi mean diameter, and ϕ_{16}, ϕ_{50}, and ϕ_{84} are the diameters in phi units corresponding with the 16th, 50th, and 84th percentiles, respectively, of the cumulative weight-per cent (coarser) curve. The results of

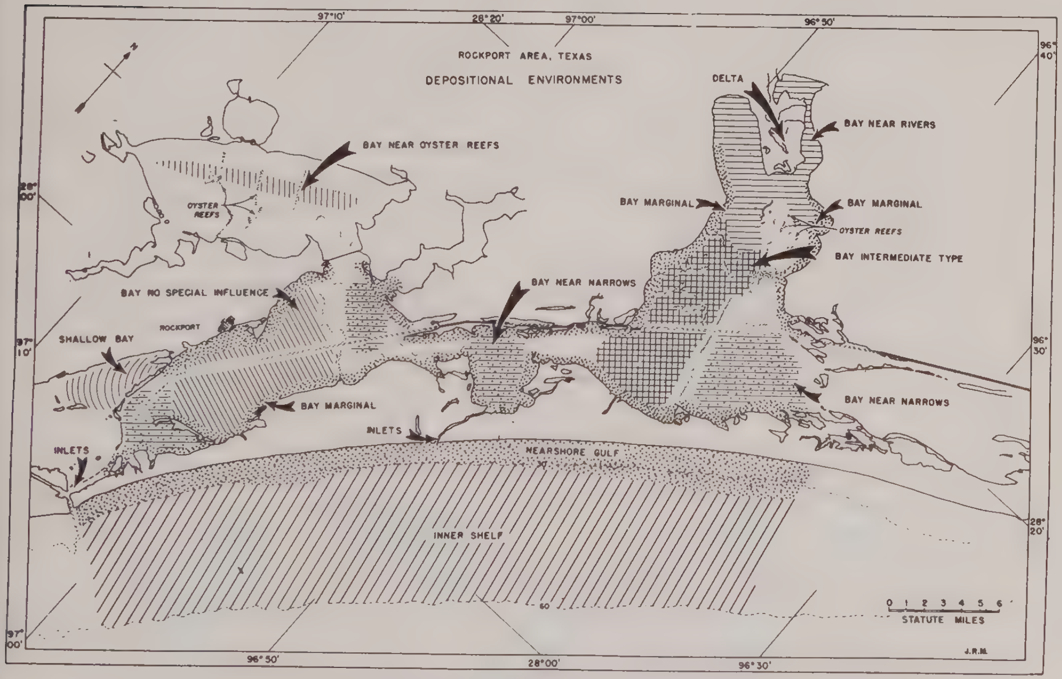
ROCKPORT AREA, TEXAS
DEPOSITIONAL ENVIRONMENTS
97°10'
28°20'
97°00'
96°50'
96°40'
DELTA
BAY NEAR RIVERS
BAY NEAR OYSTER REEFS
OYSTER REEFS
BAY MARGINAL
BAY MARGINAL
OYSTER REEFS
BAY INTERMEDIATE TYPE
BAY NEAR NARROWS
BAY NO SPECIAL INFLUENCE
ROCKPORT
SHALLOW BAY
28°00'
97°10'
96°30'
BAY MARGINAL
INLETS
INLETS
NEARSHORE GULF
BAY NEAR NARROWS
INNER SHELF
28°20'
97°00'
0 1 2 3 4 5 6
STATUTE MILES
J.R.M.
96°50'
28°00'
96°30'

FIG. 25.—Environments of deposition in Rockport area based largely on coarse-fraction analysis.

applying this means of interpreting sediments in the Rockport area are shown (Fig. 24) from the article by Inman and Chamberlain (1955).

Another method of characterizing the size of grains is with sand-silt-clay ratios, discussed previously. Triangle diagrams of the sand-silt-clay ratios for the environments of the Rockport area[9] show that the points have distinct groupings in each environment (Fig. 26). The method is of special value because the two major sources of sediment for the area are: (1) sand introduced by the longshore currents and tides coming in through the inlets, and (2) clay introduced by the streams coming into the upper bays.

Coarse-fraction analysis.—A method which is one of the most valuable for characterizing environments in the Rockport area is called "coarse-fraction analysis" (Shepard and Moore, 1954). In this method the binocular microscope is used to estimate the percentages of significant constituents in different size fractions, using the standard Wentworth size grades. The constituents considered important in the Rockport area include echinoids, Foraminifera, glauconite, ostracods, shells (mollusks *et cetera*), plants including fibers, and terrigenous minerals (land-derived minerals such as quartz, feldspar, and ferro-magnesians). In addition, aggregates, formed where various minerals or organic débris have been cemented together mostly by calcium carbonate or iron oxide, were included in the classification.

Various diagrams for presenting this information have been developed. Some of these are illustrated in Figures 27 and 28. The relation of the constituents to environments, both as they vary in different sieve sizes and in relation to the total coarse fraction, has been clearly indicated by the studies. In characterizing the environments of the Rockport area, coarse-fraction analysis is superior to grain-size analysis, because size is important largely as it is related to transportation of material of relatively uniform shape and density. A considerable percentage of the grains in the Rockport area consists of mollusk shells, Foraminifera, echinoids, and ostracods, many of which have grown in or near their place of deposition so that their size has little to do with currents or wave action. As a result, one finds coarse-grained sediment in some parts of the bays despite the fact that the area is protected from large waves and the currents are of small velocity. Similarly, plant fragments are of nearly the same specific gravity as water when introduced and therefore do not follow the laws of settling velocities. Therefore, plants can not be used in relation to sizes. The same applies to minerals, such as glauconite and pyrite, which may form in place as authigenic substances. All of these constituents have significance in relation to the environments.

The coarse-fraction method can be made more valuable by a small amount of differentiation of organisms. For example, oysters can be separated from the other mollusk shells, and Foraminifera can be classified as pelagic or benthonic, giving more usefulness to the observations. Still further differentiation must, of course, depend on the training of the observer.

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[9] See Figure 25 for the environments, and for discussion of these environments see pp. 1528–45.

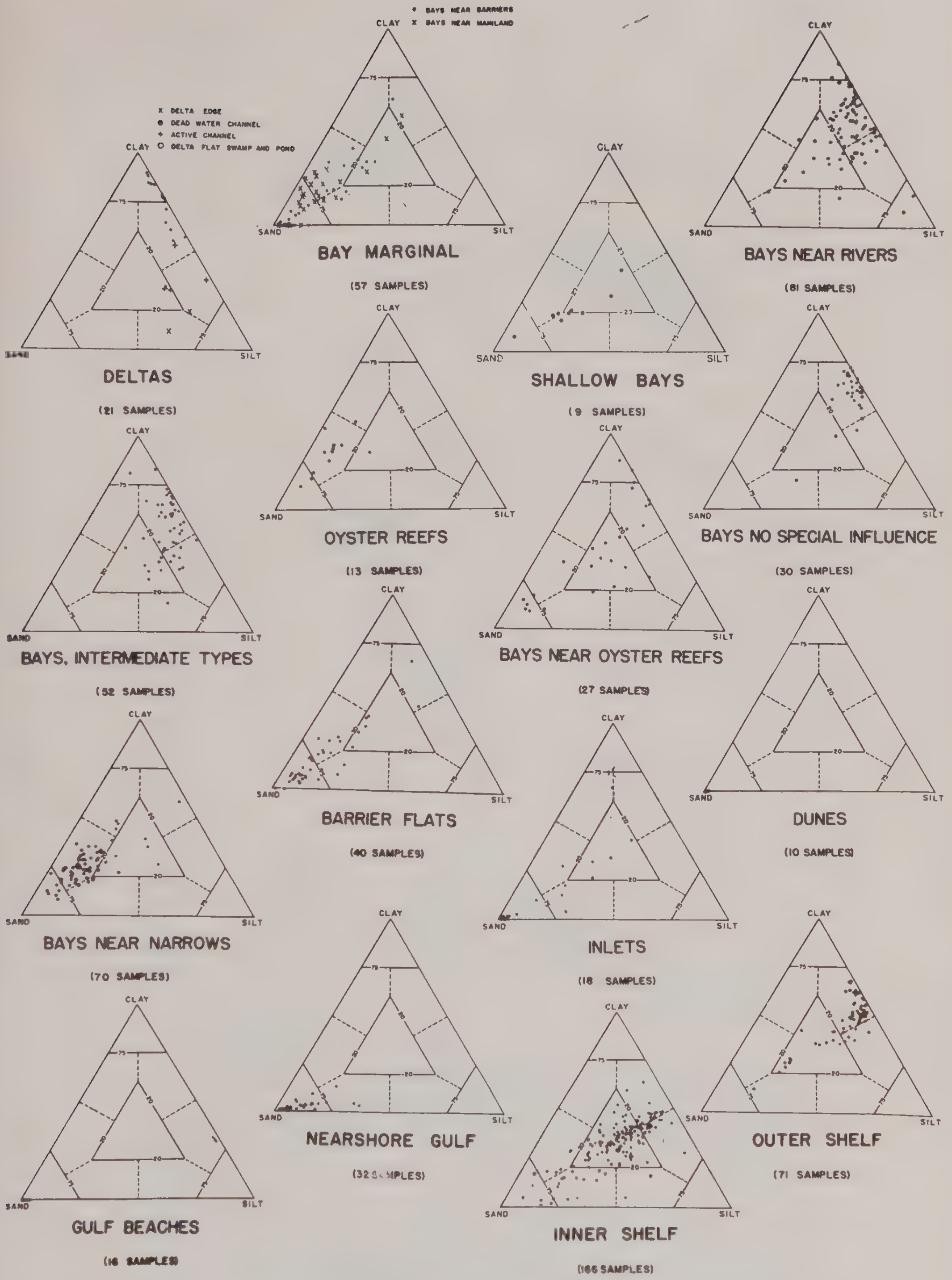

Fig. 26.—Triangle diagrams showing sand-silt-clay contents of samples in various environments indicated in Figure 25. Four subdivisions of delta environment are indicated, and two subdivisions of "bay marginal."

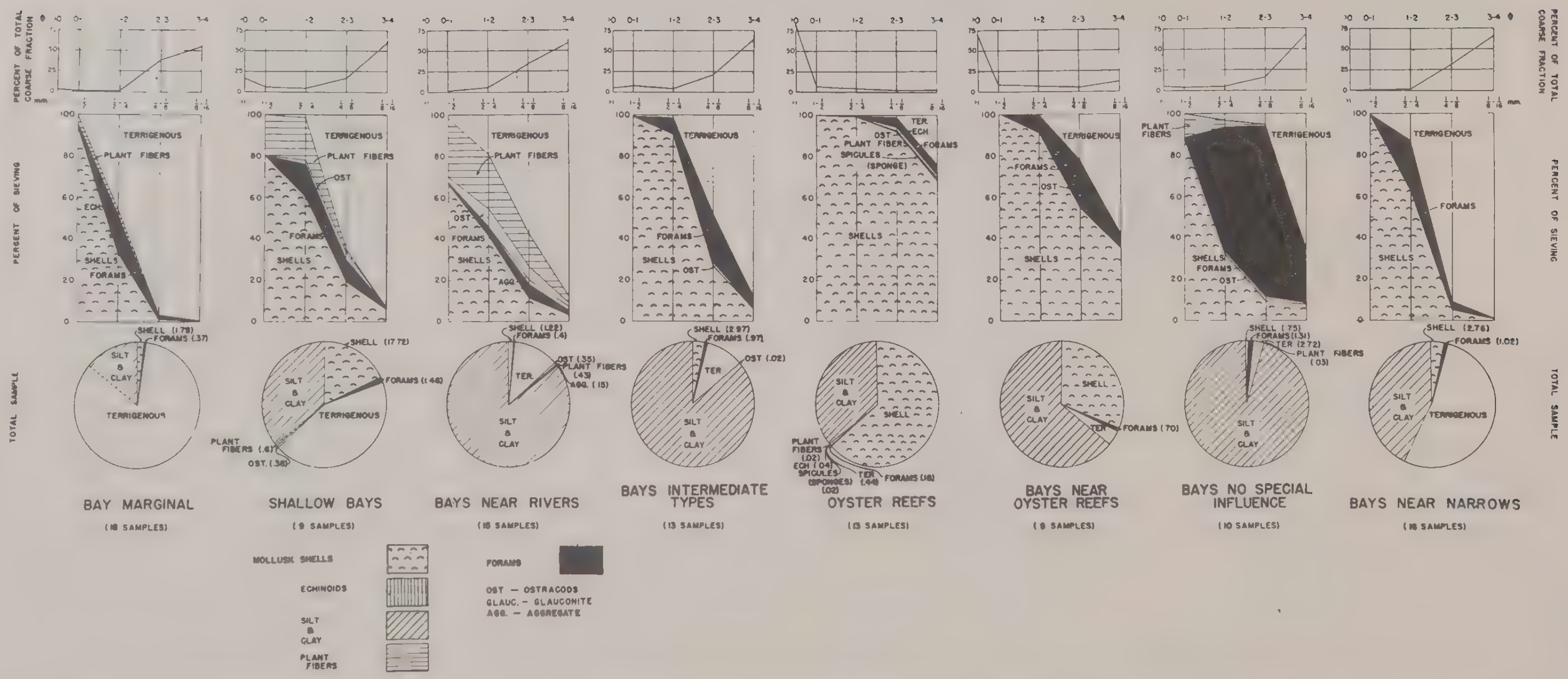

FIG. 27.—Coarse fraction of bay environments showing average percentage of material in different sizes of coarse fraction, percentages of constituents in each sieve size, and percentage of materials in total sample (shown in pie diagram along with percentage of silt and clay). Shells constitute most of part greater than 1 mm. ($>0_\phi$).

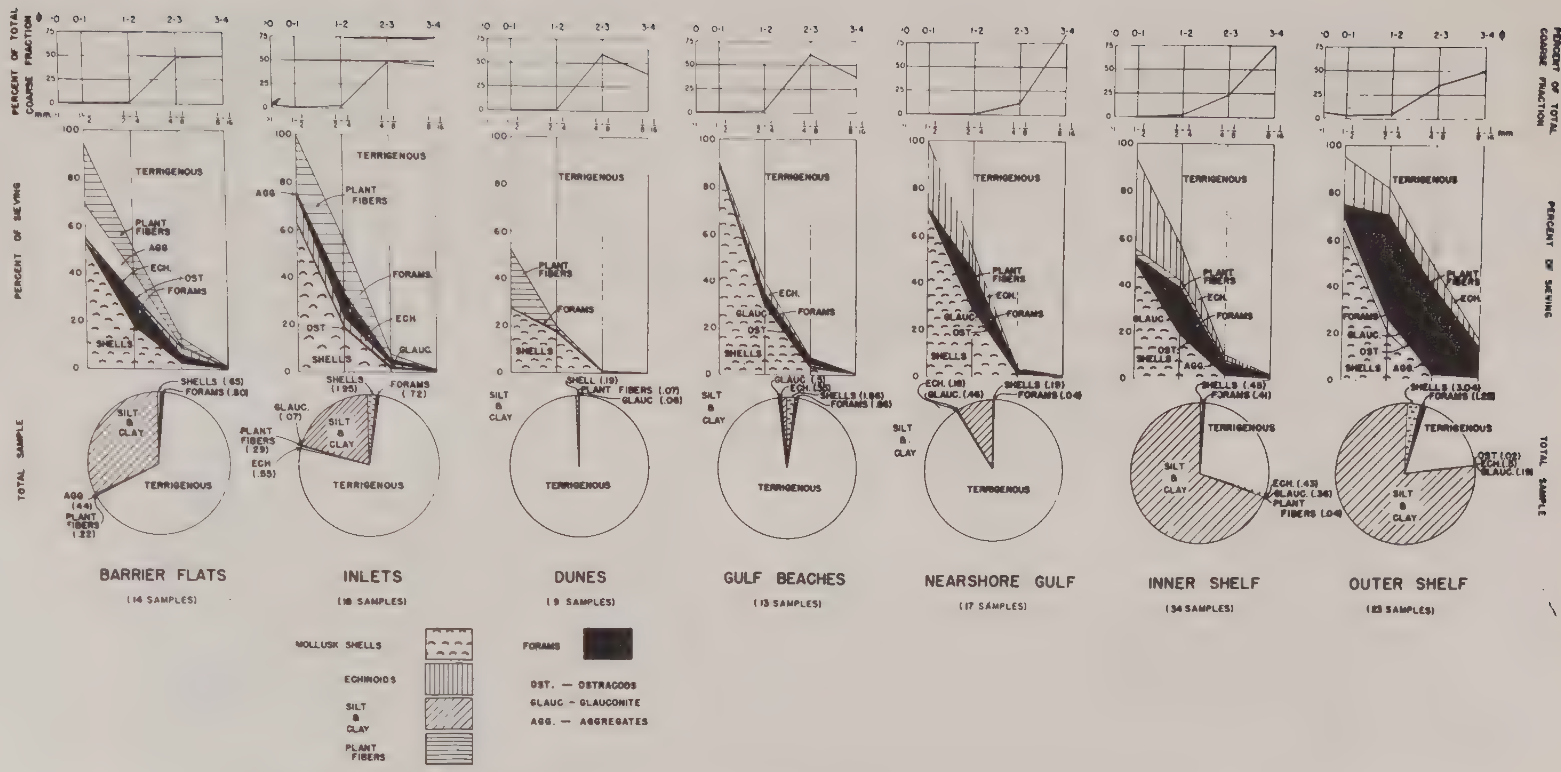

Fig. 28.—Coarse fraction of barrier island and shelf environments. Shells constitute most of part greater than 1 mm. ($>0_\phi$)

Minor internal structures.—In describing and photographing the hundreds of cores from the Rockport and Mississippi Delta areas it was noted that certain minor internal structures were characteristic of the sediments of particular environments, whereas in other environments the sediments were commonly structureless. Moore and Scruton (*ms.*, '55) made a study of these minor features and found that they could be divided essentially into two types, "layered" and "mottled" (Fig. 29). Layered structures were subdivided into "regular" and "irregular," according to the uniformity of the banding. These were found to be typical of areas where few organisms live, such as near the mouths of rivers. Mottled structures, which consist of lumps and pockets of irregular shape in a matrix of sediment of contrasting size, were found to be characteristic of zones of mixed sediments in areas with abundant mud-dwellers. These mottled structures are common in areas which have two sources of sediment. The lower bays of the Rockport area are a good example of this situation, having a silty clay source from the river and a sand source from the barrier islands. Homogeneous, structureless sediments were found in areas of only one source of a predominant size such as the deep central parts of bays and the outer shelf.

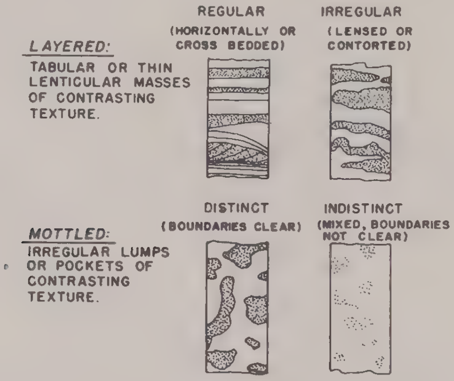
REGULAR
(HORIZONTALLY OR CROSS BEDDED)
IRREGULAR
(LENSED OR CONTORTED)
LAYERED:
TABULAR OR THIN LENTICULAR MASSES OF CONTRASTING TEXTURE.
DISTINCT
(BOUNDARIES CLEAR)
INDISTINCT
(MIXED, BOUNDARIES NOT CLEAR)
MOTTLED:
IRREGULAR LUMPS OR POCKETS OF CONTRASTING TEXTURE.

FIG. 29.—Minor internal structures in cores of Rockport area. In part related to effect of organisms indicated in Figure 13.

The principal methods of formation of minor internal structures are believed to be variations in competence of a transporting agent from a single source in the case of layered structures, and the work of organisms in destroying layering in the case of the mottled type. Burrowing animals are capable of creating, as well as of destroying, minor structures (Fig. 13). Irregular layering and mottled structures are examples of types which may be formed by local current action induced by organic activity such as syphoning.

Mineral analysis.—The sand-size minerals of the Rockport area consist principally of quartz with lesser amounts of feldspar. Samples from various parts of the area and from the rivers contributing to the area were counted for quartz, plagioclase, and potash feldspar by Harry Lusk, using a staining technique (Gabriel and Cox, 1929). The results were very uniform and showed no appreciable trend. Quartz averaged 65.2 per cent, plagioclase 22.5 per cent, and potash feldspar 12.3 per cent. By way of contrast, the light minerals of the shelf of the east-central Gulf are much higher in quartz, whereas typical counts on the west coast of the United States show feldspars more abundant than quartz.

The heavy minerals are scarce, generally less than one per cent of the sand fraction. Heavy-mineral studies of the sediments of the bays, barrier islands, and open shelf of the area have been made by M. N. Bramlette and D. M. Poole. They found that the bays are characterized by a suite of stable minerals consisting of black opaques (including leucoxene), tourmaline, garnet, zircon, and rutile, with the addition of staurolite near the Guadalupe Delta. Epidote is fairly abundant in the bays but is a non-diagnostic mineral. Only a very small amount of hornblende is present in the upper bays, but it increases nearer the barrier islands and reaches a maximum on the Gulf beaches. The southern part of Aransas Bay does not follow this general pattern, having very few heavy minerals, of which biotite mica is the most abundant.

The major source of the stable minerals in the Rockport area is the Guadalupe River. Hornblende was probably introduced by the Colorado River on the north of the area and was carried south along the beaches or even along the continental shelf by longshore currents (Bullard, 1942).

The studies by Bramlette and Poole show that hornblende is an important mineral on the continental shelf, being widely distributed but most abundant near shore. Hornblende is probably swept into the bays by hurricane storm tides and by strong winds. Other abundant minerals on the shelf are black opaques (including leucoxene), epidote, tourmaline, garnet, and zircon.

Roundness studies.—The roundness of grains is dependent on the cleavage which they possess and on the amount of abrasion due to transportation. However, the average roundness of a deposit may be strongly influenced by selective transportation of rounded grains. Since quartz is the dominant mineral in most of the sands of the Rockport area, a comparison of the rounding of quartz grains has been used in differentiation of environments. Because rounding is also a function of size, it was decided that grains of only the $\frac{1}{8}$–$\frac{1}{16}$-mm. size, which are very abundant in all of the area, would be used for this purpose. The roundness was determined by two methods. One, proposed by Powers (1953), determines an average roundness by comparing grains with photographs and obtaining a geometric mean of the numbers of various grades of roundness in each sample. The other method devised in part by Beal (Beal and Shepard—in press) consists of photographing the grains and comparing the pictures with the roundness chart of Krumbein (1941), thus removing the difficulty of third-dimensional aspects which comes from looking at the grains under a microscope. Both methods have

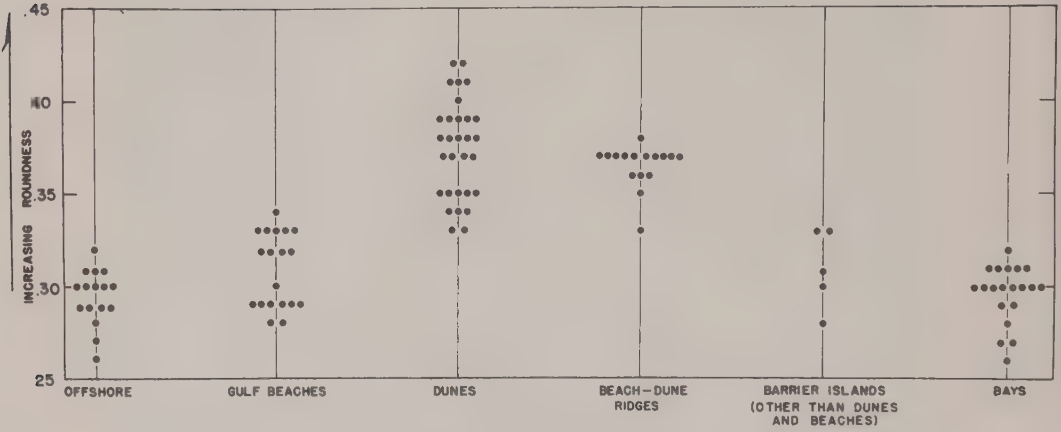

FIG. 30.—Index of rounding in several environments. Dune sands are much more rounded than those of other environments.

produced similar results, and show a consistent difference in the rounding of grains of the same size in dunes and in other environments (Fig. 30). The dune sands are distinctly more rounded as has been shown in previous studies (Mac-

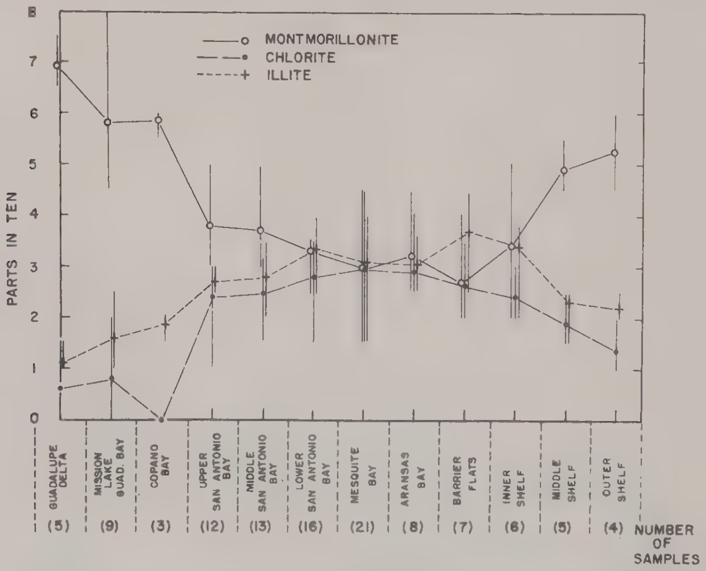

FIG. 31.—From data supplied by R. E. Grim and Wm. D. Johns, showing relationship of relative abundance of three clay minerals to environments of Rockport area. Montmorillonite, which decreases going down the bays, increases in crossing continental shelf.

Carthy, 1935). The method also indicates that the sand in the so-called "beach" ridges on both islands has a roundness of dune type even at as much as 7 feet below the surface.

Clay-mineral analysis.—The use of X-ray diffraction analysis and differential thermal analysis serves to show the nature of the clay minerals that are found in various parts of the Rockport area (Grim and Johns, 1955). The ratios of the principal minerals, montmorillonite, illite, and chlorite, are computed in probable parts of ten of the total clay minerals (Fig. 31). When these analyses have been averaged for different environments they show some striking contrasts although they also give a certain amount of overlap, particularly in different parts of the bays. These contrasts are probably related to the changing salinity from the bay heads to marine conditions in the open Gulf. Grim and Johns conclude that these differences are chiefly the result of early diagenesis rather than differential sedimentation. Since the clay minerals are relatively stable after this period of early diagenesis, these variations can be used in helping diagnose environments of depositions.

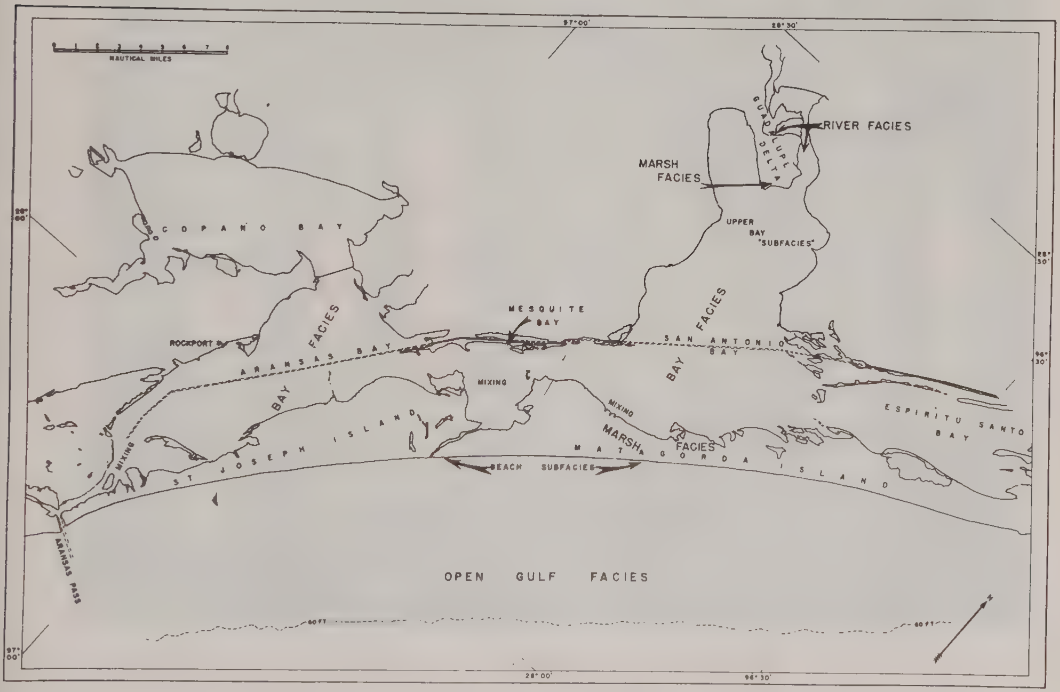
NAUTICAL MILES
0 1 2 3 4 5 6 7 8
97°00'
28°30'
28°00'
28°30'
96°30'
97°00'
28°00'
96°30'
COPANO BAY
ROCKPORT
ARANSAS BAY
BAY FACIES
MIXING
ST JOSEPH ISLAND
ARANSAS PASS
MESQUITE BAY
MIXING
GUADALUPE DELTA
RIVER FACIES
MARSH FACIES
UPPER BAY "SUBFACIES"
SAN ANTONIO BAY
BAY FACIES
MIXING
MARSH FACIES
MATAGORDA ISLAND
BEACH SUBFACIES
ESPIRITU SANTO BAY
OPEN GULF FACIES
60 FT
60 FT
N

FIG. 32.—Facies of Foraminifera in Rockport area. Other organisms show similar facies relation.

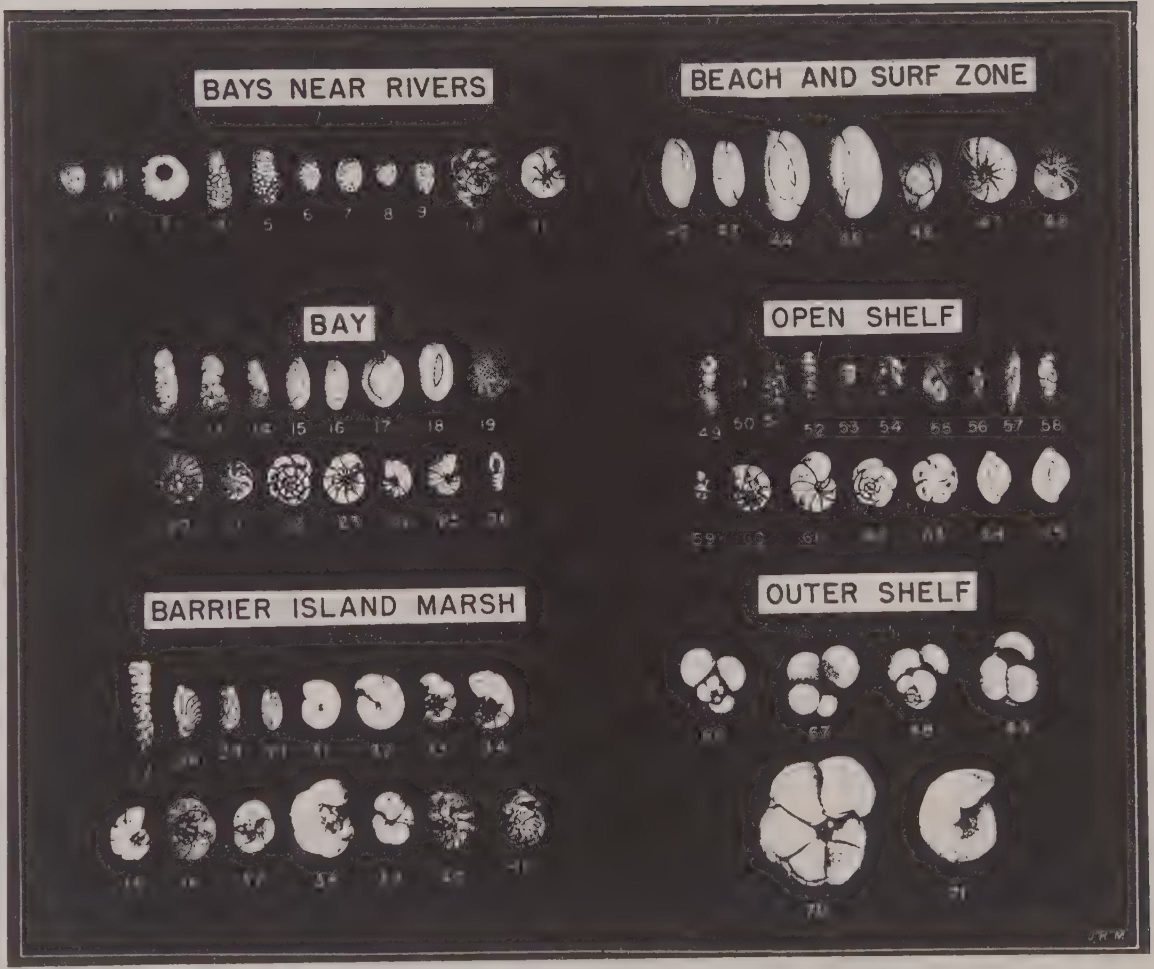
BAYS NEAR RIVERS
5
6
7
8
9
BEACH AND SURF ZONE
BAY
15
16
17
18
19
23
OPEN SHELF
49
50
52
53
54
55
56
57
58
59
61
BARRIER ISLAND MARSH
OUTER SHELF
67
J.R.M.

FIG. 33.—Representatives of assemblages of Foraminifera in various facies of Rockport area. Localities for these facies are indicated in Figure 32, except for outer shelf. Prepared by F. B Phleger and Francès L. Parker.

1. *Lagunculina vadescens* Cushman and Bronnimann
2. *Lagunculina* sp.
3. *Leptodermella variabilis* Parker
4, 5. *Proteonina lagenaria* (Berthelin)
6, 7. *Urnulina compressa* Cushman
8. *Urnulina* sp. A.
9. *Urnulina* sp. B.
10, 11. "*Rotalia*" *beccarii* (Linne) variant C.
12, 13. *Ammobaculites salsus* Cushman and Bronnimann variants
14. *Ammobaculites* sp. A.
15, 16. *Quinqueloculina poeyana* d'Orbigny
17, 18, *Quinqueloculina rhodiensis* Parker
19. *Elphidium gunteri* Cole
20. *Elphidium galvestonense* Kornfeld
21. *Elphidium matagordanum* (Kornfeld)
22, 23. "*Rotalia*" *beccarii* (Linné) variant A.
24, 25, 26. *Palmerinella palmerae* Bermudez
27. *Pseudoclavulina gracilis* Cushman and Bronnimann
28. *Ammoastuta inepta* (Cushman and McCulloch)
29, 30. *Miliammina fusca* (H. B. Brady)
31, 32. *Arenoparrella mexicana* (Kornfeld)
33, 34, 35. *Jadammina polystoma* Bartenstein and Brand
36, 37. *Trochammina comprimata* Cushman and Bronnimann
38, 39. *Trochammina inflata* (Montagu)
40, 41. *Discorinopsis aguavoi* (Bermudez)
42, 43. *Quinqueloculina* cf. *compta* Cushman
44, 45. *Quinqueloculina seminulum* (Linné)
46. *Guttulina australis* (d'Orbigny)
47, 48. *Elphidium incertum mexicanum* Kornfeld
49. *Bigenerina irregularis* Phleger and Parker
50, 51. *Nouria polymorphinoides* Heron-Allen and Earland
52, 53. *Rectobolivina advena* (Cushman)
54. *Reussella atlantica* Cushman
55. *Guttulina australis* (d'Orbigny)
56, 57. *Virgulina pontoni* Cushman
58, 59. *Virgulina spinicostata* Phleger and Parker
60, 61. *Cibicidina strattoni* (Applin)
62, 63. "*Rotalia*" *rolshauseni* Cushman and Bermudez
64, 65. *Quinqueloculina lamarckiana* d'Orbigny
66, 67. *Globigerina bulloides* d'Orbigny
68, 69. *Globigerinoides rubra* (d'Orbigny)
70. *Globorotalia menardii* (d'Orbigny)
71. *Globorotalia truncatulinoides* (d'Orbigny)

BIOLOGICAL METHODS

One of the most important factors in identifying sedimentary environments is the study of the fauna and flora which inhabit these environments. Many animals are sensitive to temperature, salinity, and water turbulence. Others may be controlled by the type of food material, predation, the bottom sediment, and other physical and chemical variables. Therefore, the shells or tests of the invertebrates, which are commonly found in sediments, constitute valuable clues to conditions during their life.

Foraminifera.—A study of 320 equal-size samples from the bays, the marshes,

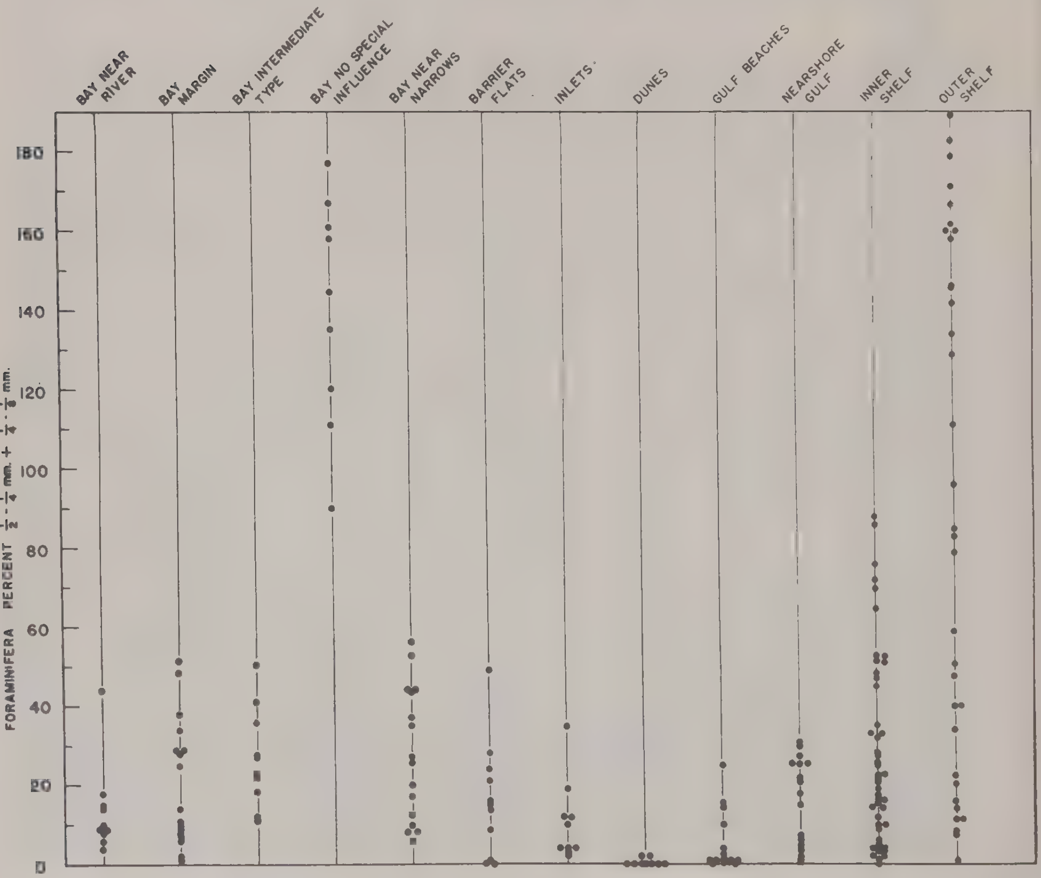

FIG. 34.—Abundance of Foraminifera in two sieve sizes (combined) as related to environments of Rockport area. Foraminifera of outer shelf are largely pelagic and should, therefore, not be confused by their abundance with Foraminifera in "bay no special influence" environment.

and the open Gulf (including beaches) has resulted in a publication entitled "Ecology of Foraminifera from San Antonio Bay and Environs, Southwest Texas," by Parker, Phleger, and Peirson (1953). Their studies show that there are four principal bio-facies consisting of river, marsh, bay, and open Gulf,[10] and two subfacies, including beaches and the upper portion of San Antonio Bay (Figs. 32 and 33). They also recognize the occurrence of mixed faunas in the lower bays, particularly near the inlets. The relation of floods and of marine invasions during periods of low run-off are considered in connection with these faunas.

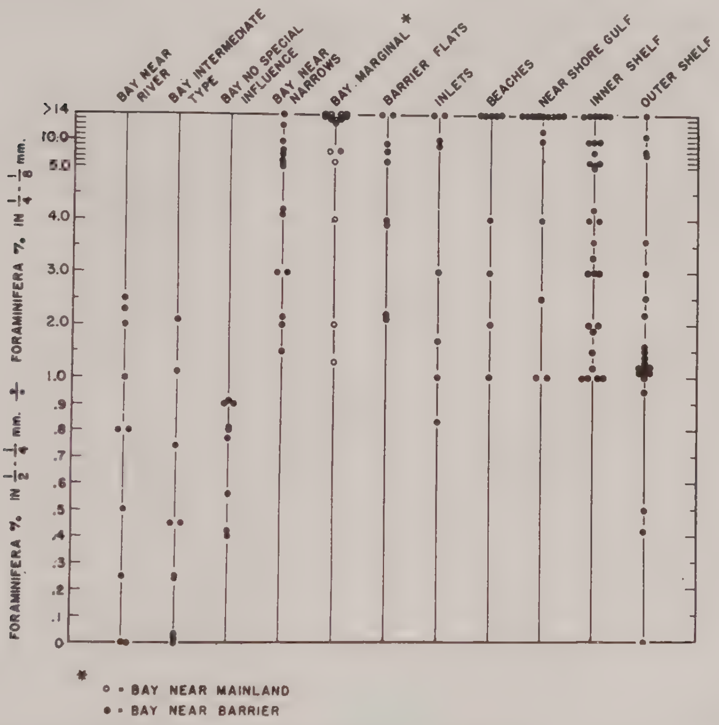

FIG. 35.—Ratio between Foraminifera in ½–¼-mm. to Foraminifera in ¼–⅛ mm. sieve sizes as related to environments of Rockport area. ½–¼ mm. Foraminifera predominate in environments related to barrier islands, whereas smaller Foraminifera are more abundant in bay environments.

In addition to the counts made by the Marine Foraminifera Laboratory at Scripps Institution, the coarse-fraction studies by the present writers have shown some of the gross relationships of the abundance of Foraminifera to other sediment constituents in the different environments. These are shown in Figures 34–36. Figure 34 shows the relation of environments to the sum of percentages of Foraminifera in the $\frac{1}{2}$–$\frac{1}{4}$-and $\frac{1}{4}$–$\frac{1}{8}$-mm. size fractions. One of the bay environments and the outer shelf have particularly high counts. Figures 35 and 36 show the relationships of the ratios of Foraminifera percentages in different size fractions to the environments. These ratios are also clearly related to environments. An exceptional abundance of Miliolidae was observed in the $\frac{1}{2}$–$\frac{1}{4}$-mm. fractions in the barrier island environments. These results are mentioned again in discussing environmental characteristics.

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[10] Various divisions occur also on the shelf but these are still being studied by the Scripps Foraminifera Laboratory.

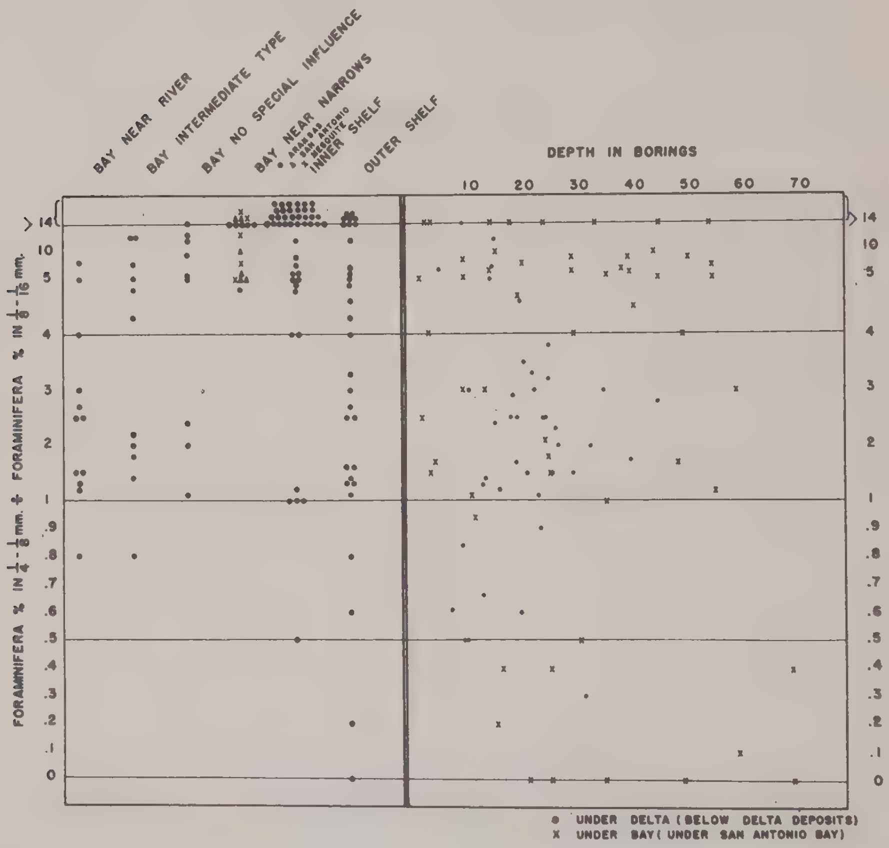

FIG. 36.—Relationships similar to those of Figure 35 for next smaller sieve. Trend in this comparison is same as previous. Right-hand part of figure indicates that Foraminifera obtained in samples from bay borings are related to bay types with respect to size distribution.

There can be little doubt that the Foraminifera are one of the most sensitive indicators of environments. This has been found in the Rockport area and in most other areas where marine sediments have been studied.

Ostracoda.—The Ostracoda have been studied by F. M. Swain who has worked largely with collections from San Antonio Bay, the barrier island marshes, and the shallow open Gulf in the vicinity. The report by Swain (1955) gives a sequence of bio-facies which is similar to those described for the Foraminifera. It includes (1) a fluvial and pro-delta facies which is particularly well developed in the low-salinity Mission Lake as well as along the river channels and in some parts of the delta; (2) a bay facies which has the following sub-facies: (a) mid-bay, (b) lower-bay and marginal, and (c) barrier island marsh; and (3) open Gulf facies. Swain shows that the development of these facies is largely dependent on the salinity differences but also on available food supply and perhaps on the type of bottom. Swain recognized 47 species, one variety, and one sub-species, and notes that 15 of these are known to occur as fossils, eight of which are present as far back as Miocene. Some of the diagnostic Ostracoda are illustrated in Figure 37. Doris Malkin Curtis has also studied the divisions of the Ostracoda on the deeper shelf. She found that significant breaks in the fauna occur at approximately 20- and 50-fathom depths.

Macro-organisms.—The study of the macro-organisms during the first 1½ years of the project was conducted under the direction of J. Wyatt Durham and for the next 2 years under Joel W. Hedgpeth. Most of the collecting was done by R. H. Parker and E. L. Puffer with some help from W. K. Emerson. A brief paper concerning the mollusks of the oyster-reef biotope of the bays has been published by Puffer and Emerson (1953). A series of subdivisions of the faunal communities was made by Puffer which largely corresponds with that reported earlier by Harry S. Ladd (1951). This has subsequently been expanded and modified by Parker (Figs. 38, 39).

The macro-organisms show the same general relationship to salinity revealed by the Foraminifera and Ostracoda facies. The effect of the recent change of salinity has been pronounced on the macro-organisms causing open Gulf forms, such as echinoderms, corals, and certain Gulf mollusks, to move into the lower bays (Parker, 1955). In turn, a species of pelecypod, *Rangia cuneata*, and a gastropod, *Littoridina sphinctostoma*, have almost disappeared from the low-salinity waters of San Antonio Bay coincident with the increasing salinity. The Rangias that remain have a smaller than average size which may indicate either that this mollusk can not attain maturity or that its adults are dwarfed in the higher-salinity waters now present in San Antonio Bay (Parker, 1955). During the years 1951–1953, the oyster reefs in Aransas Bay, normally composed of the common bay oyster, *Crassostrea virginica*, were dominated by the high-salinity Gulf oyster, *Ostrea equestris* (Puffer and Emerson, 1953, and Parker, 1955). In general, the bay macro-organism assemblages have approximately the same faunal boundaries as those of the Ostracoda and Foraminifera, with the exception of the

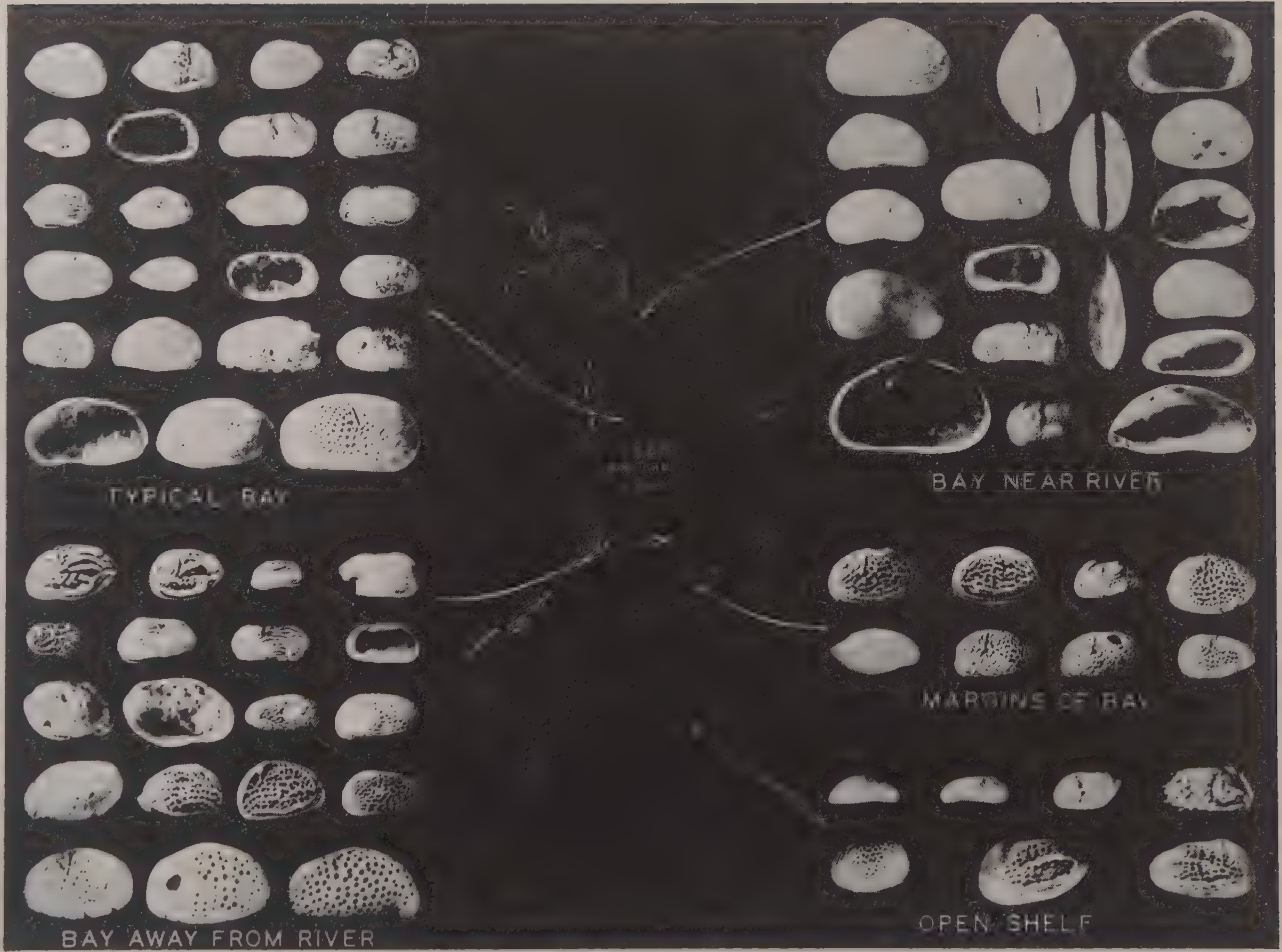
TYPICAL BAY
BAY NEAR RIVER
MARGINS OF BAY
BAY AWAY FROM RIVER
OPEN SHELF

FIG. 37.—From Swain (1955), showing characteristic ostracods in several environments of Rockport area.

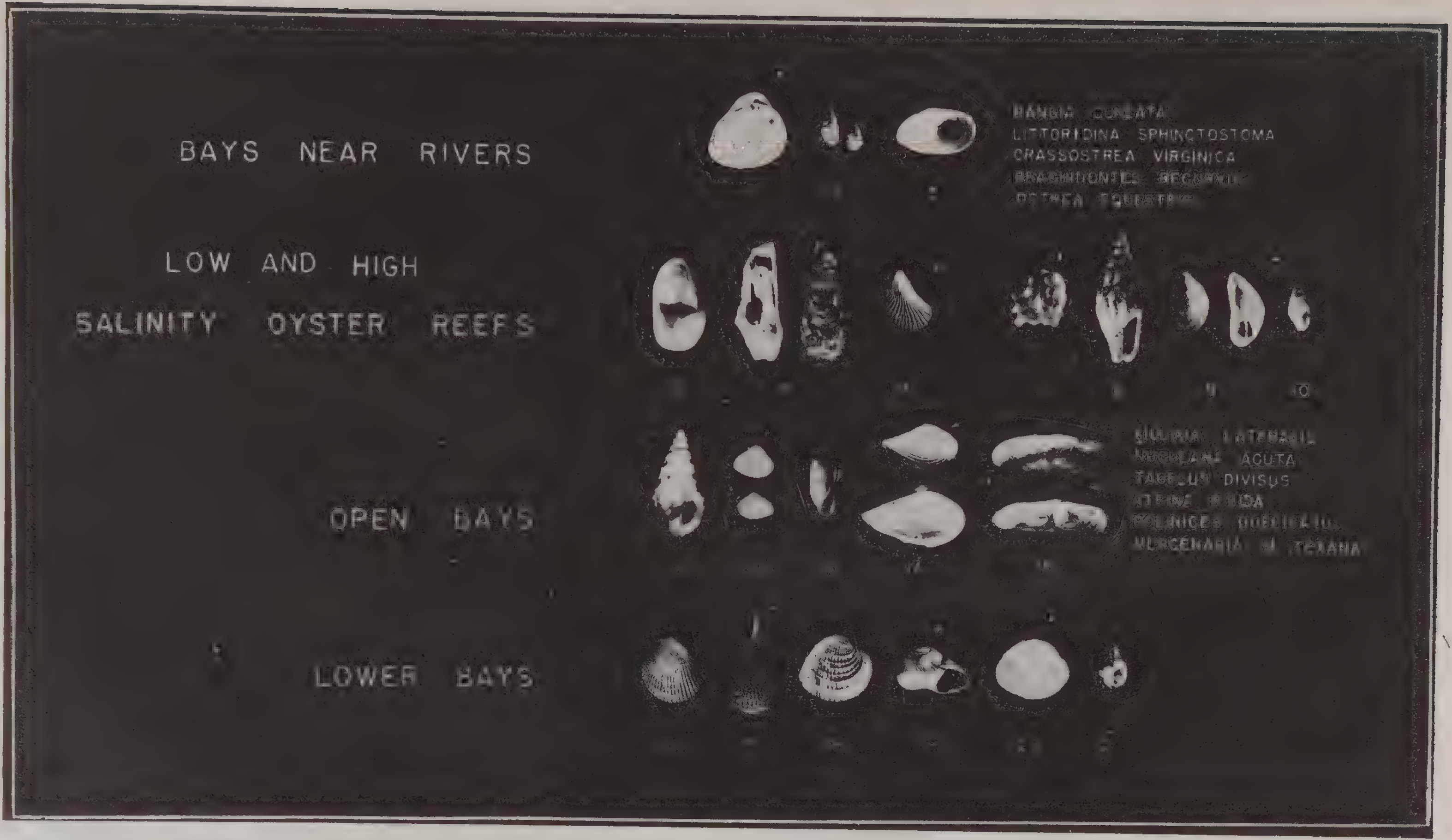
BAYS NEAR RIVERS
LOW AND HIGH
SALINITY OYSTER REEFS
OPEN BAYS
LOWER BAYS
RANGIA CUNEATA
LITTORIDINA SPHINCTOSTOMA
CRASSOSTREA VIRGINICA
BRACHIDONTES RECURVUS
OSTREA EQUESTRIS
10
MULINIA LATERALIS
NUCULANA ACUTA
TAGELUS DIVISUS
ATRINA RIGIDA
POLINICES DUPLICATUS
MERCENARIA M. TEXANA

FIG. 38.—(See legend page 1517).

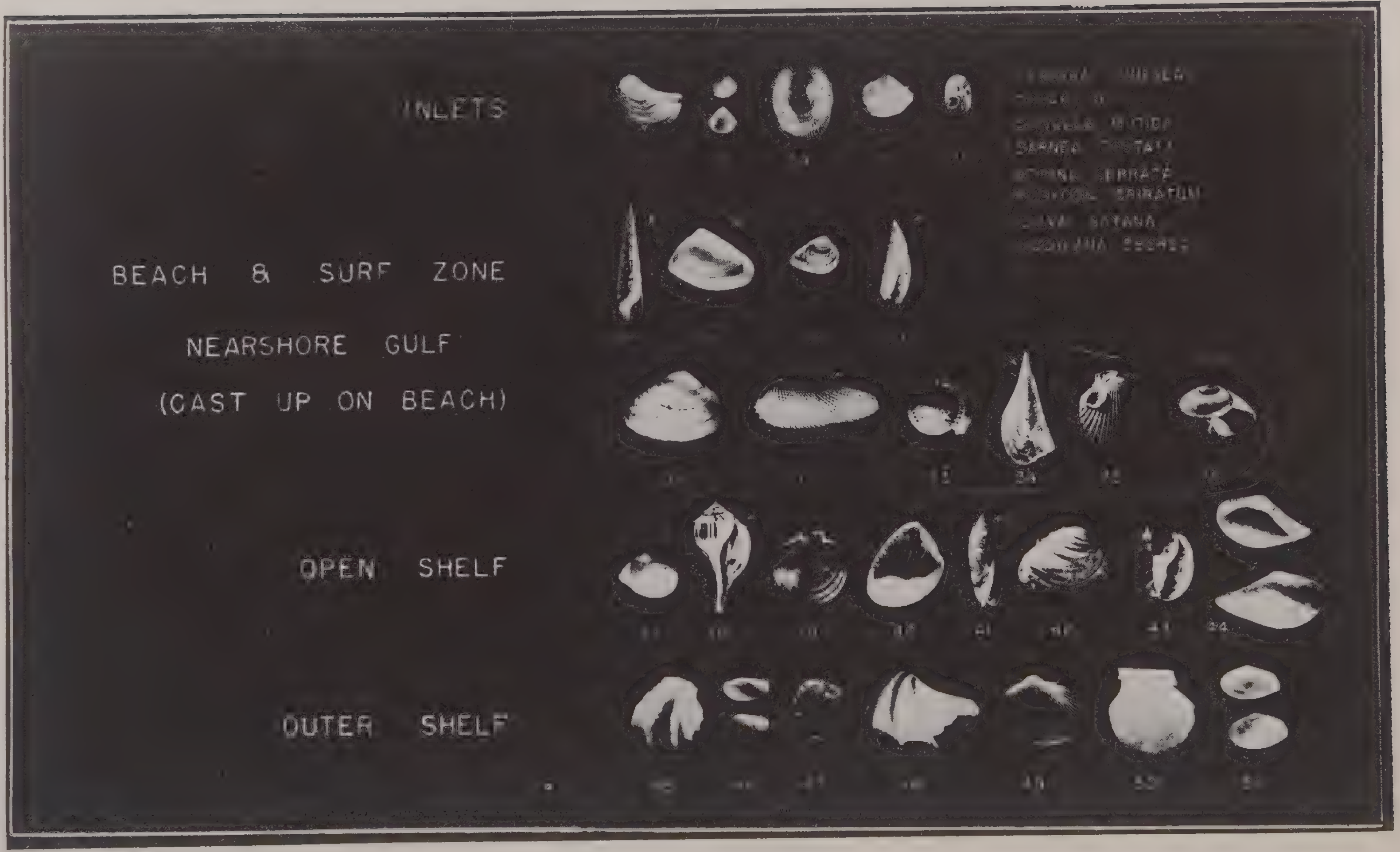
INLETS
BEACH & SURF ZONE
NEARSHORE GULF
(CAST UP ON BEACH)
OPEN SHELF
OUTER SHELF

Fig. 39.—(See legend page 1517).

FIGS. 38 and 39.—Macro-organisms representative of Rockport environments. Although many names are included in diagram, complete list of organisms by number is appended. Some of the characteristic mollusks of Texas sedimentary environments prepared by R. H. Parker. Scale variable, but paper in preparation will give correct scale for all species shown here.

1. *Rangia cuneata* Gray, 1831
2. *Littoridina sphinctostoma* Abbott and Ladd, 1951
3. *Macoma mitchelli* Dall, 1895
4. *Crepidula plana* Say, 1822
5. *Crassostrea virginica* Gmelin, 1791
6. *Brachidontes recurvus* Rafinesque, 1820
7. *Ostrea equestris* Say, 1834
8. *Anachis avara semiplicata* Stearns, 1873
9. *Brachidontes exustus* Linné, 1758
10. *Mitrella lunata* Say, 1826
11. *Nassarius acutus* Say, 1822
12. *Mulinia lateralis* Say, 1822
13. *Retusa canaliculata* Say, 1827
14. *Nuculana acuta* Conrad, 1832
15. *Tagelus divisus* Spengler, 1794
16. *Trachycardium muricatum* Linné, 1758
17. *Atrina rigida* Solander, 1786
18. *Chione cancellata* Linné, 1767
19. *Polinices duplicatus* Say, 1822
20. *Mercenaria mercenaria texana* Dall, 1902
21. *Nassarius vibex* Say, 1822
22. *Pandora trilineata* Say, 1822
23. *Crassinella martinicensis* d'Orbigny, 1842
24. *Siphonaria pectinata* Linné, 1758
25. *Tellidora cristata* Récluz, 1842
26. *Diodora cayenensis* Lamarck, 1822
27. *Terebra cinerea* Born, 1778
28. *Donax*, sp. (*Donax texasiana* Philippi, 1847 and *D. tumida* Philippi, 1848 are present, although confusion exists as to exact species in Texas)
29. *Anomalocardia cuneimeris* Conrad, 1846
30. *Olivella mutica* Say, 1822
31. *Spisula solidissima raveneli* Conrad, 1831
32. *Barnea costata* Linné, 1758 (recently changed to *Cyrtopleura costata*, although *Barnea* is in more general use)
33. *Architectonica nobilis* "Bolten" Roding, 1798
34. *Atrina serrata* Sowerby, 1825
35. *Aequipecten irradians concentricus* Say, 1822
36. *Janthina janthina* Linné, 1758
37. *Quadrans lintea* Conrad, 1837
38. *Busycon spiratum* Lamarck, 1816
39. *Pecten papyraceus* Gabb, 1873
40. *Nucula proxima* Say, 1822
41. *Oliva sayana* Ravenel, 1834
42. *Chione clenchi* Pulley, 1952
43. *Phalium granulatum* Born, 1778
44. *Nuculana eborea* Conrad, 1846
45. *Verticordia ornata* d'Orbigny, 1846
46. *Yoldia solenoides* Dall, 1881
47. *Chama congregata* Conrad, 1833
48. *Cuspidaria ornatissima* d'Orbigny, 1846
49. *Papyridea soleniformis* Bruguiére, 1789
50. *Cyclopecten nanus* Verrill and Bush, 1897
51. *Phylloda squamifera* Deshayes, 1854

oyster-reef assemblage with its characteristic substrate composed of shell, predominantly *Crassostrea virginica*. The shallow, high-salinity bays near inlets, such as Redfish Bay, also appear to have a distinctive molluscan fauna (mostly small gastropods) which are not reflected in the Foraminifera and Ostracoda biofacies.

The mollusks on the shallow part of the continental shelf (out to 10 fathoms) in the Gulf of Mexico are similar to those found at present in lower Aransas Bay and Lydia Ann Channel, except for about five to ten species characteristic of the open Gulf. However, the surf zone of the Gulf beach has a distinct population composed of the pelecypod, *Donax* sp., and two gastropods, *Terebra cinerea* and *Olivella mutica*, all of which are capable of boring rapidly into the hard sand close to the beach. On the other hand, the macro-organisms found on the shelf in 10–11 fathoms to at least 60 fathoms are quite distinct and seldom found on the beaches, even after heavy storms (Fig. 39). Echinoderms are also very characteristic of the open Gulf from the surf zone to the shelf edge, although some species are found in the inlets where salinity conditions are similar to those of the open Gulf.

Microfossils.—The microfossils were studied from 59 samples obtained in the Rockport area. This study was made by Arthur E. LeBlanc as a master thesis problem under the direction of L. R. Wilson at the University of Massachusetts. These samples covered most of the fifteen depositional environments of the Rockport area and thus give interesting information concerning the environmental patterns of the microfossils. Counts were made of the micro-foraminifera, hystrichosphaerids, fungus spores, non-arborescent spores and pollen, and arborescent pollen in each of these samples. Also a considerable break-down of the species and genera was made. This material is discussed in the thesis by LeBlanc.

In summarizing the pertinent points of the investigation, the following significant correlations appear (Table I).

TABLE I. AVERAGE NUMBER OF MICRO-FOSSILS PER UNIT VOLUME FOR ENVIRONMENT

Environment (Fig. 25)	*No. of Samples*	*Micro-foraminifera*	*Hystrichosphaerids*	*Fungus Spores*	*Non-arborescent Spores and Pollen*	*Arborescent Pollen*
Bays near mainland	9	62.06	1.02	11.04	18.02	7.07
Bays near rivers	13	32.7	.62	52.9	13.6	5.24
Bays near oyster reefs	6	44.2	3.5	3.84	12.2	13.9
Bays intermediate type	17	51.2	1.71	19.9	7.3	9.66
Bays no special influence	13	36.3	2.62	12.0	8.47	7.85
Bays near narrows	18	71.5	1.06	8.16	7.44	9.34
Bays near barriers	7	33.5	1.0	10.2	12.7	9.15
Barrier flats	9	49.9	1.0	42.4	53.0	19.42
Inlets	3	15.3	2.6	10.0	7.6	33.0
Gulf beach	6	.33	.33	.33	.83	.33
Nearshore gulf	1	57.0	3.0	10.0	8.0	32.0
Inner shelf	8	25.9	2.0	10.8	5.75	15.0
Outer shelf	5	418.0	4.4	8.6	4.0	22.2

1. The fungus spores are most abundant in and around the Guadalupe Delta and on the barrier flats.
2. The micro-foraminifera are common in many environments especially in the middle and lower bays where they increase away from the river mouths and on the outer shelf. In the deeper parts of Aransas Bay (Bays, no special influence), however, the micro-foraminifera are distinctly less abundant than in the shoaler bays.
3. On the barrier flats of the islands the non-arborescent spores and non-arborescent pollens reach their highest abundance, and the arborescent pollen is most abundant in the inlets and in the near-shore Gulf.
4. The beach sands are almost devoid of microfossils.
5. The fungus spores and non-arborescent spores decrease outward across the shelf in contrast to the micro-foraminifera, which decrease only out to about 40 feet, beyond which they increase enormously.

The changes in abundance of micro-foraminifera with depth in core are interesting since they show some of the same variations that are indicated by the Foraminifera. Thus the general increase in micro-foraminifera which is indicated a short distance below the bottom in the bay samples is duplicated by the increase of the Foraminifera (p. 1571).

CHEMICAL METHODS

Surface variations.—In using the environmental boundaries established by the coarse-fraction and other methods (Fig. 25), the chemical data in the top 20 cm. of sediment were averaged and compiled into Figure 40. For convenience, water content and grain size are shown in this same figure. This figure indicates the importance of clay-size particles in regulating chemical characteristics of the sediments as shown by the relationships of the organic carbon, pH, Eh (the apparent EMF of the sediment determined with a platinum calomel electrode combination), and water-content curves to the percentage of clay in each of the environments. An increase in clay content is associated with similar increases in water content and organic carbon content which in turn result in lower Eh values and higher pH. An exception to this pattern is caused by the specialized conditions in the "bay near barrier island" environment[11] where a lowering of clay content is not accompanied by a corresponding decrease in organic carbon. The Eh value, on the other hand, does rise considerably. This condition is probably an effect of the shallow, aerated waters surrounding the islands.

The $CaCO_3$ contents, determined manometrically by CO_2 assay, are also influenced by clay content, but another variable, the distance from the Guadalupe River, is important causing a steady decrease in $CaCO_3$ with distance from the river (Figs. 41, 42). The reason for the high content in upper Guadalupe Bay and near the delta is that particulate calcium carbonate material is being introduced into the Guadalupe and San Antonio River basins, probably from the Austin chalk and various Lower Cretaceous and Paleozoic formations. This particulate matter was observed in the petrographic microscope examination made by M. N. Bramlette of the samples from San Antonio Bay. The influence of the Guadalupe

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[11] "Bay near barrier" and "bay near mainland" are subdivisions of the "bay marginal" environment of Figure 25.

River is again shown by low pH values in the "bay near river" environment. This is the only point on the graph at which pH is not a reflection of Eh. Evidently the water introduced by the river (pH 6.62) has a stronger influence on pH than have the relatively low Eh and high carbonate values.

Calcium carbonate is expressed in two ways in Figure 40. One is "visual

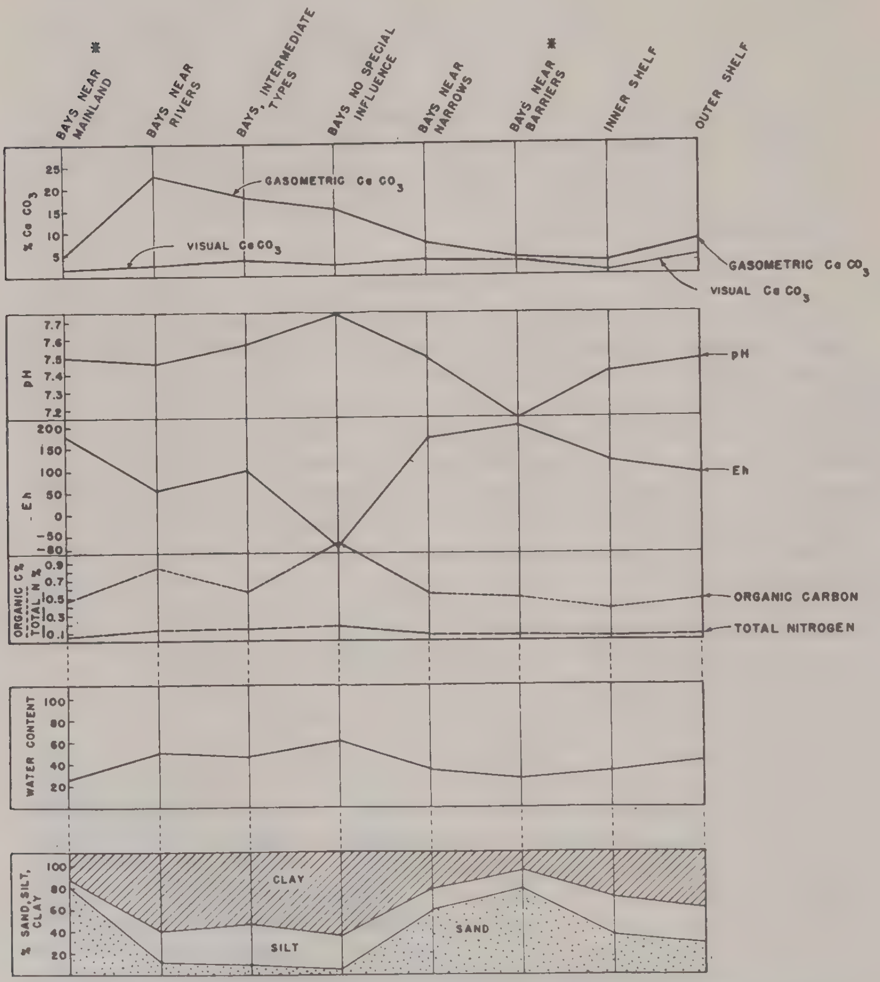

FIG. 40.—Chemical data, water content, and sand-silt-clay relations of environments in Rockport area. Visual $CaCO_3$ is based on estimates from coarse-fraction analyses. Asterisk indicates subdivisions of bay marginal environments.

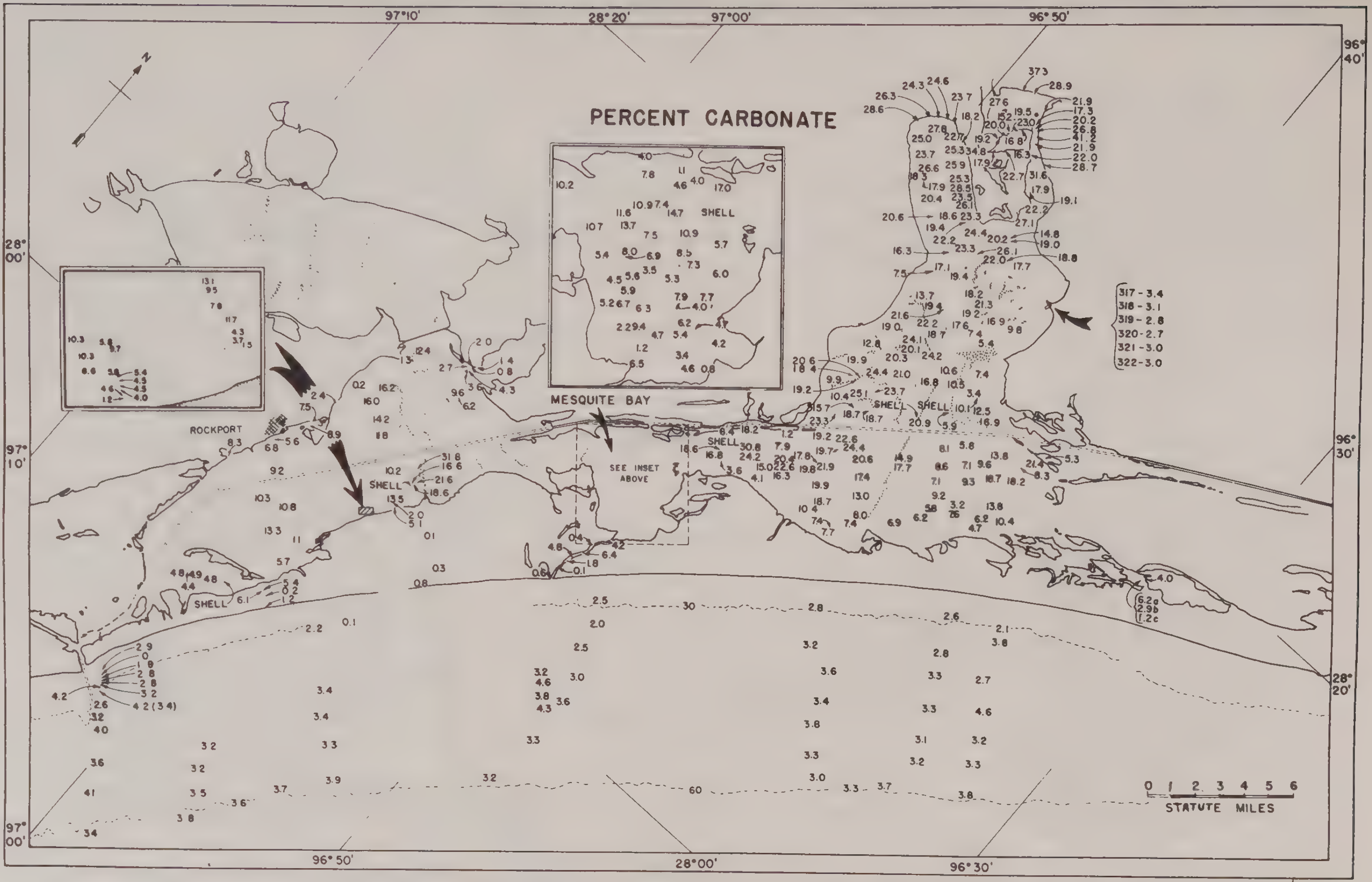
PERCENT CARBONATE
MESQUITE BAY
ROCKPORT
SEE INSET ABOVE
SHELL
317 - 3.4
318 - 3.1
319 - 2.8
320 - 2.7
321 - 3.0
322 - 3.0
0 1 2 3 4 5 6
STATUTE MILES
N
97°10'
28°20'
97°00'
96°50'
96°40'
28°00'
97°10'
96°30'
28°20'
97°00'
96°50'
28°00'
96°30'

FIG. 41.—Percentage of carbonate of samples in Rockport area based on gasometric analysis. High percentages found in and around Guadalupe delta and low percentages in near-shore environments.

$CaCO_3$" which was obtained from coarse-fraction (greater than 0.062 mm. in size) estimates of percentage of mollusk shells, Foraminifera, Ostracoda, and echinoid fragments in the various environments. The other is the gasometric chemical analysis of the carbonate constituents of the sediments. In general the larger shells were picked out as much as possible before making the chemical analyses so that the results only partly reflect the importance of the macro-organisms in the different samples, and show largely the calcium carbonate of the finer material.

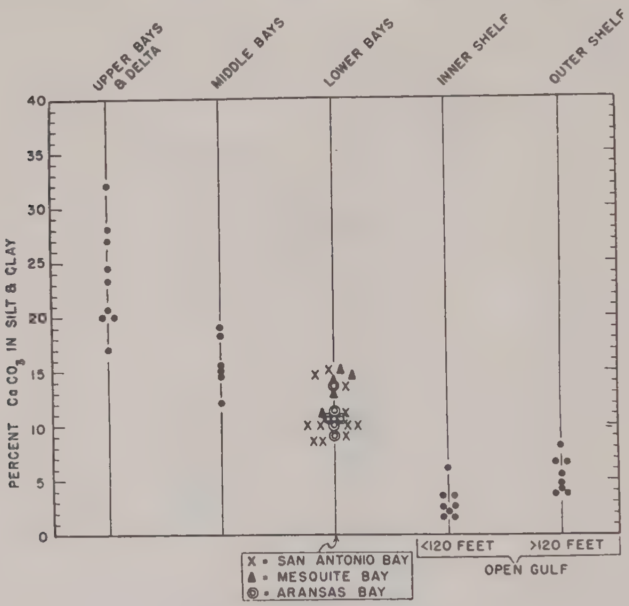

FIG. 42.—Percentages of $CaCO_3$ in silt and clay fractions related to environments. Slight increase shown in samples of outer shelf (see also Fig. 43).

It is notable that the two curves more nearly coincide in the environments where river-borne clay constitutes a small percentage of the sediments ("bays near mainland" and "bays near barriers"), and in the open Gulf environments far from a river source. The quantities of carbonate shown by chemical analysis in these environments must be partly the result of "visual carbonate." A rough estimate of what may be primarily inorganic $CaCO_3$ can therefore be obtained by subtracting the visual from the gasometric $CaCO_3$ values. In order to eliminate the effect of such organisms as Foraminifera, Ostracoda, echinoids, and the smaller mollusks, the coarse fraction was entirely removed from a series of samples so that the carbonate analysis was made of the fine fraction alone. The results of the two methods seem to indicate approximately the same thing, as can be

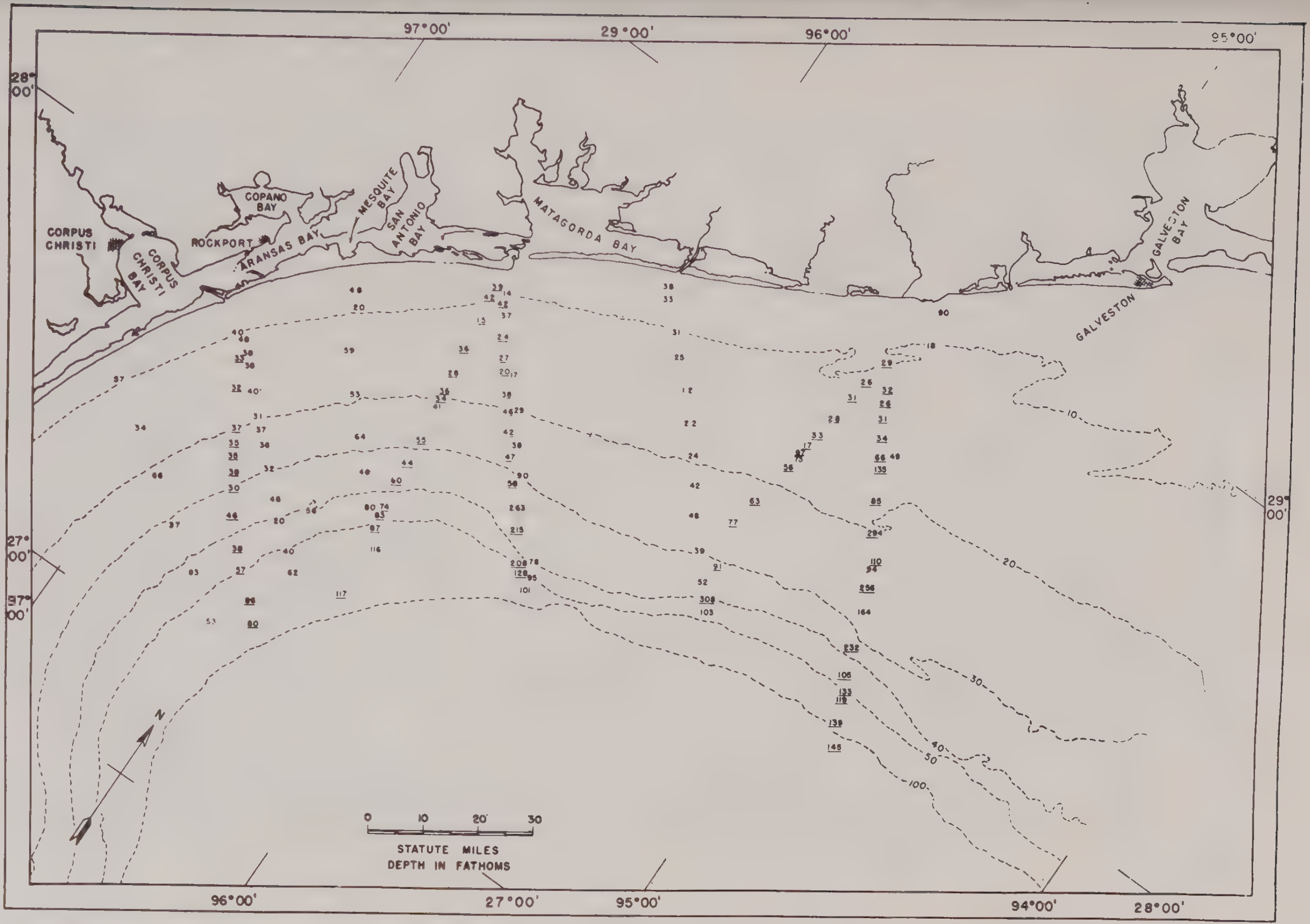
97°00'
29°00'
96°00'
95°00'
28°00'
27°00'
29°00'
94°00'
CORPUS CHRISTI
CORPUS CHRISTI BAY
ROCKPORT
COPANO BAY
ARANSAS BAY
MESQUITE BAY
SAN ANTONIO BAY
MATAGORDA BAY
GALVESTON
GALVESTON BAY
N
10
20
30
40
50
100
0
10
20
30
STATUTE MILES
DEPTH IN FATHOMS

FIG. 43.— $CaCO_3$ content in parts per thousand on shelf off central Texas area. Underlined figures are from Trask (1953). General increase in $CaCO_3$ content with increasing distance from shore.

seen by comparison of Figure 41, which shows the percentage of carbonate from the entire sample in all but the offshore area, with Figure 42 showing percentage of carbonate from the silt and clay fraction only. Both figures show that the calcium carbonate is very high near the Guadalupe Delta, decreases down San Antonio Bay, and remains fairly constant in Mesquite and Aransas bays except near the two inlets where it is very low. Similarly, the calcium carbonate is low in most of the continental shelf sediments, largely less than 5 per cent (Fig. 43). The values show a decided increase on the outer shelf, reaching up to 16 per cent in the analyses by the writers and 31 per cent in one of the values obtained in the same area by Trask (1953).

It may be noted that the lowest values of calcium carbonate are found in some of the inlets and on the "barrier flats" of the islands. Furthermore, most of the open Gulf samples have a lower percentage than the bay samples. The exceptions to this rule are found in some samples in the "bays near inlets" or on the bay slopes near the barrier islands. The calcium carbonate is distinctly low on the southeast side of San Antonio Bay, suggesting the influence of an inlet, although in this case the inlet has an indirect connection to the open Gulf through Espiritu Santo Bay.

Continuity of pH with depth.—In addition to the surface measurement of pH, readings were made at various depths in cores from four of the major environments. Figure 44 shows that there is a distinct difference between the river sediment and the group from the bays and open Gulf. It is notable that at all core depths the readings from bays are less than those of the open Gulf. There is only a small separation between bay and open Gulf environments. The gradation from river to open Gulf is reasonable inasmuch as the river water has a very much lower pH than has the Gulf water, and therefore an intermediate pH should be the average of the bays.

Spectrochemical analysis.—One of the most successful chemical methods of differentiating sedimentary environments has been the analysis of spectro-chemical data. Four long cores from the Guadalupe River, San Antonio Bay, Aransas Bay, and the open Gulf of Mexico, 20 miles offshore (Fig. 44), have been subjected to these analyses at representative depths in the core. The oxides, K_2O, Na_2O, TiO_2, Fe_2O_3, and Al_2O_3, have been plotted against depth in core and compared with curves of clay content from these same cores.[12] It was found that the oxide curves generally were of the same shape as that of the clay content and must therefore be related to the clay minerals in the sediments.

A small increase in K_2O and a significant decrease in Al_2O_3 are notable as the stations increase in distance from the river source. The ratio of Al_2O_3/K_2O, plotted against depth at the four localities (Fig. 44), is apparently a valuable criterion for determining relative distance from the source. It is of significance that the values of this ratio are relatively constant with depth at any one of the locali-

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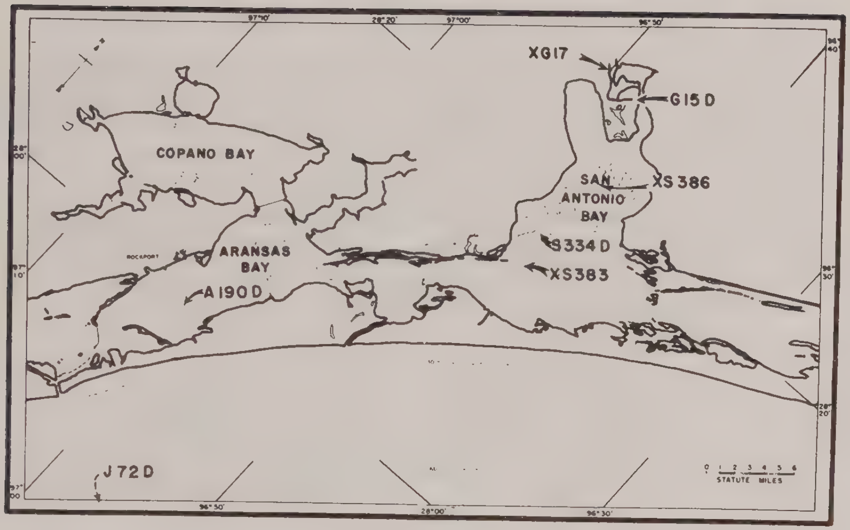
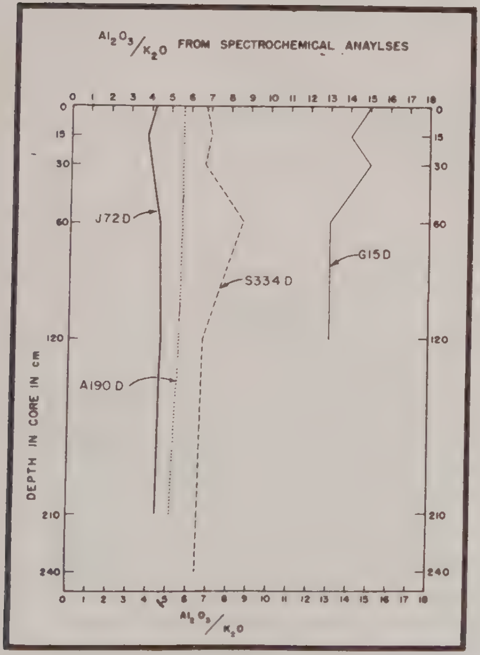
[12] The relation to depth in core is discussed mostly under Diagenesis pp. 1578–91; see also Figures 70–72.

A.


COPANO BAY
ARANSAS BAY
ROCKPORT
SAN ANTONIO BAY
XG17
G15 D
XS 386
S334 D
XS383
A190 D
J72 D
97°10'
28°20'
97°00'
96°50'
28°00'
96°30'
0 1 2 3 4 5 6
STATUTE MILES

B.



C.

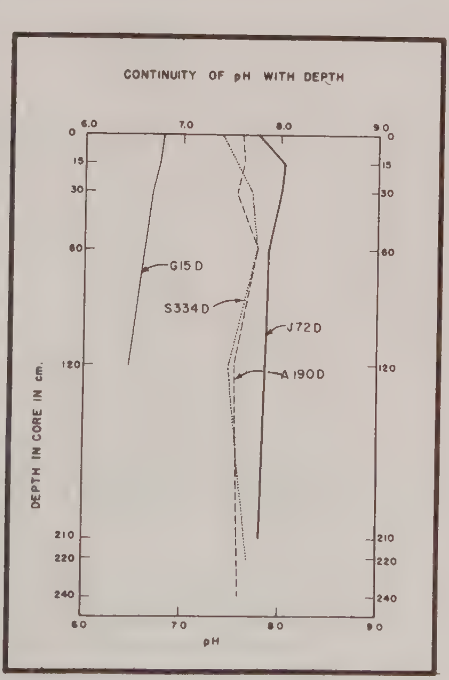


FIG. 44A.—Locations of samples for chemical and spectrochemical analyses. Variation with depth in core indicated in lower diagrams.

FIG. 44B.—Variations of Al_2O_3/K_2O with environment and continuity with depth.

FIG. 44C.—Variations of pH with environment and continuity with depth.

ties. Evidently the spectrochemical analysis of these sediments gives good empirical evidence of the relative distance from their source. This may be related to rates of deposition or other physical factors.

BACTERIOLOGICAL METHODS

The main emphasis in the bacteriology study by Contois has been placed upon an attempt to establish relationships between environmental characteristics, as defined by the bacterial groups and geochemical parameters of these sediments. It is hoped that some of the latter may be established thereby as meaningful criteria of environmental characteristics and processes.

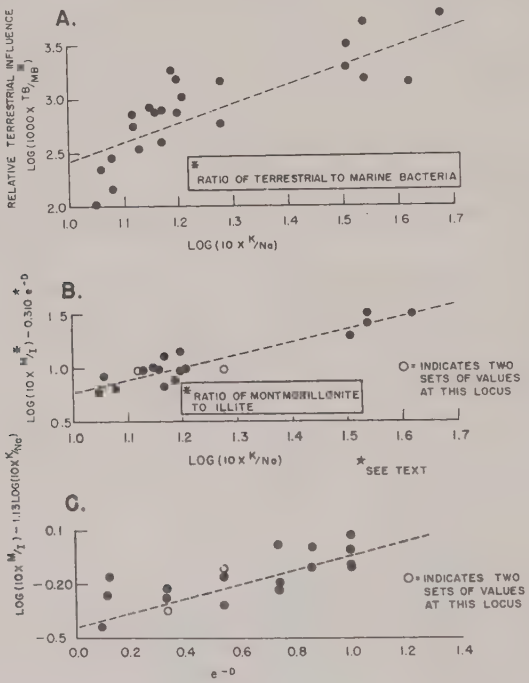


FIG. 45.—A. Correlation between terrestrial influence and sodium-potassium ratio. B. Partial regression of potassium-sodium ratio upon montmorillonite-illite ratio. C. Partial regression of depth in sediment upon montmorillonite-illite ratio.

A statistically significant correlation ($r \neq 0.78$, $P < 0.01$) exists between terrestrial influence in environments as measured by the ratio of terrestrial bacteria to marine bacteria ($\log(1000 \times TB/MB)$) and the ratio of potassium to sodium ($\log(10 \times K/Na)$) of total sediment samples. This relationship, shown in Figure

45A, was established from the study of cores respectively from the Guadalupe Delta (G15), middle San Antonio Bay (S334), Aransas Bay (A190), and the offshore Gulf (J72) (Fig. 44). Samples were taken from the 0, 15, 30, 60, 120, and 240-cm. depths within the cores. These parameters apparently are not correlated with depth or time of burial of the sediment. Hence, the possibility is presented of employing ratios of potassium to sodium as a means of determining terrestrial influence in older sediments at the time of their deposition.

Further analyses of these and other data provided by Grim and Johns indicate that the ratio of montmorillonite to illite ($\log(10 \times M/I)$) in these sediments can be expressed as a function of terrestrial influence and depth or (more probably) of time of burial of the sediment. These results indicate that the relative abundance of the two clay minerals at time of deposition in one locality is controlled by terrestrial influence. However, once deposited, the montmorillonite undergoes a slow transformation into illite. Figure 45B shows the regression of potassium /sodium ratios upon montmorillonite/illite ratios, independent of depth. Figure 45C depicts montmorillonite/illite ratios, independent of terrestrial influence, as a function of depth. In each instance, the variable of depth is employed in the form e^{-D} where e is the base of natural logarithms and D is the depth in decimeters. If it can be shown that the transformation of montmorillonite to illite is a function of time, it may be possible to utilize montmorillonite/illite ratios as a means of determining deposition rates.

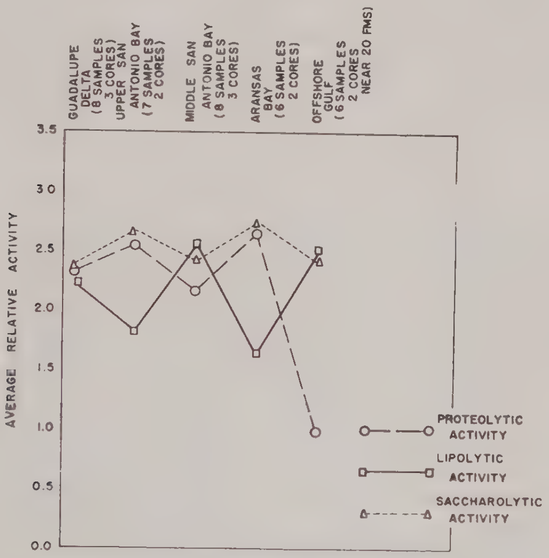


FIG. 46.—Relations between bacterial activities and Rockport environments.

An inverse correlation has been found between lipolytic activity and proteolytic activity of samples. This relationship also apparently holds in various localities in the Rockport area as is illustrated in Figure 46. In this figure, the relative activity was obtained by averaging the results of all analyses of samples from the 0–10-foot depths in the various localities.

An inverse correlation between lipolytic activity and saccharolytic activity as well as a positive correlation between saccharolytic activity and proteolytic activity apparently is indicated also (Fig. 46). In the latter two cases, however, no statistically significant relationship was found between these parameters in individual samples.

The full significance of these relationships is not clear at this time but the data indicate fundamental differences between early diagenesis of the organic matter in certain of the localities.

DISTINCTIVE MODERN ENVIRONMENTS

ENVIRONMENTS OF ROCKPORT AREA

The sedimentary environments which have been recognized in the Rockport area, largely through the coarse-fraction studies, are indicated in Figure 25. In addition to the delta, eight distinct subdivisions have been made of the bay environment, four of the barrier island environment, and three of the continental shelf. It is not yet known whether all of these sixteen environments can be recognized elsewhere along the Texas coast, but there are indications that some of the subdivisions are general, not only along the Texas coast but in many similar areas including most of the Gulf coast from Texas to Florida.

Some of the environments in the Rockport area have gradational rather than exact boundaries. The characteristics of each sediment sample within any one of the subdivisions are not exactly the same but in most respects they are remarkably similar. Although the subdivisions have been based to a very large extent on the relative abundance of the constituents of the coarse fractions (Figs. 27, 28), some use also has been made of physical and biological characteristics of the sediments in making these subdivisions. It may be noted that the subdivisions are not the same as those suggested for different classes of organisms (Fig. 32), nor do they conform exactly with those suggested by the size parameters (Fig. 24), although actually the various systems of subdividing the Rockport area have much in common. In the following description of the sixteen sedimentary environments, the characteristics which are related to size analyses, and to mineral and organic composition, are included where they appear to be of significance. It is suggested that in reading the following description of the environments frequent comparison be made to Figures 26–28.

DELTA ENVIRONMENT

The Guadalupe Delta sediments have not been studied as much as those of the other environments but the size analysis of twenty-one samples and the coarse-fraction examination of ten of these have shown that there are special influences which cause four distinct types: flowing channel, dead-water channel, delta flat or swamp, and delta marginal. The triangle diagram for delta sediments in Figure 26 shows the sand-silt-clay ratios of these four sub-environments. It is notable that clay is high and sand is very low in the dead-water channels and on the flats. In the flowing channels of the main river silt is abundant, much more common than in the bays. At the delta edge, silt is still more abundant and sand occurs in appreciable amounts as also in two of the flowing channel deposits. The coarse-fraction studies showed abundant wood fibers in most samples along with calcareous aggregates. Ostracoda occur in appreciable amounts in about half of the samples. Foraminifera are very scarce but a few of the samples have appreciable numbers, most of these have apparently been reworked from older formations. A great abundance of Foraminifera in the two delta-margin samples is attributed to a local concentration by the waves breaking on the delta edge. Pyrite is abundant in a few of the samples.

BAY ENVIRONMENTS

Bay marginal.—Most of the bay shores have sand sediments, although at a short distance away from shore the silt and clay commonly become important. The nearshore zone, which has been included in "bay marginal," extends topographically to the base of the slope where there is a decided change in the character of the sediment in most places. This is shown, for example, in the profiles of Figure 47. On this slope the sand commonly constitutes close to 80 per cent of the deposit, and of this somewhat more than 90 per cent consists of terrigenous minerals. Shells occur but are relatively rare, commonly not more than one per cent. Similarly, Foraminifera are scarcer than in the other bay environments. The sorting of the sediments is good in this zone although it falls off abruptly at the base of the slopes into the bays.

Shallow bays.—"Shallow bays" are here defined as bays in which the water is less than about 3 feet deep but where the shoalness is not due to the delta of an entering river. Since this excludes Mission Lake, the principal "shallow bay" of the area is Redfish Bay where the water is generally less than 2 feet deep. Redfish Bay has sediment which is distinct from that of the "bay marginal." The sand content is distinctly lower, only about 64 per cent, of which a little more than half is terrigenous. Silt is slightly more abundant than clay. Shells are much more abundant than in the "bay marginal," constituting about 28 per cent of the coarse fraction. Among these shells there are large numbers of the gastropods, Cerithidea, Cerithium, and Bittium. Also the Foraminifera average 2 per cent, which is higher than in the "bay marginal" zone. Both ostracods and plant fibers are better represented than in most bay environments. The plants consist largely of marine vegetation which abounds on the bay floor.

Although most of the data come from Redfish Bay, samples from Little Bay, just southwest of Rockport, have similar material. The few available samples

(843)

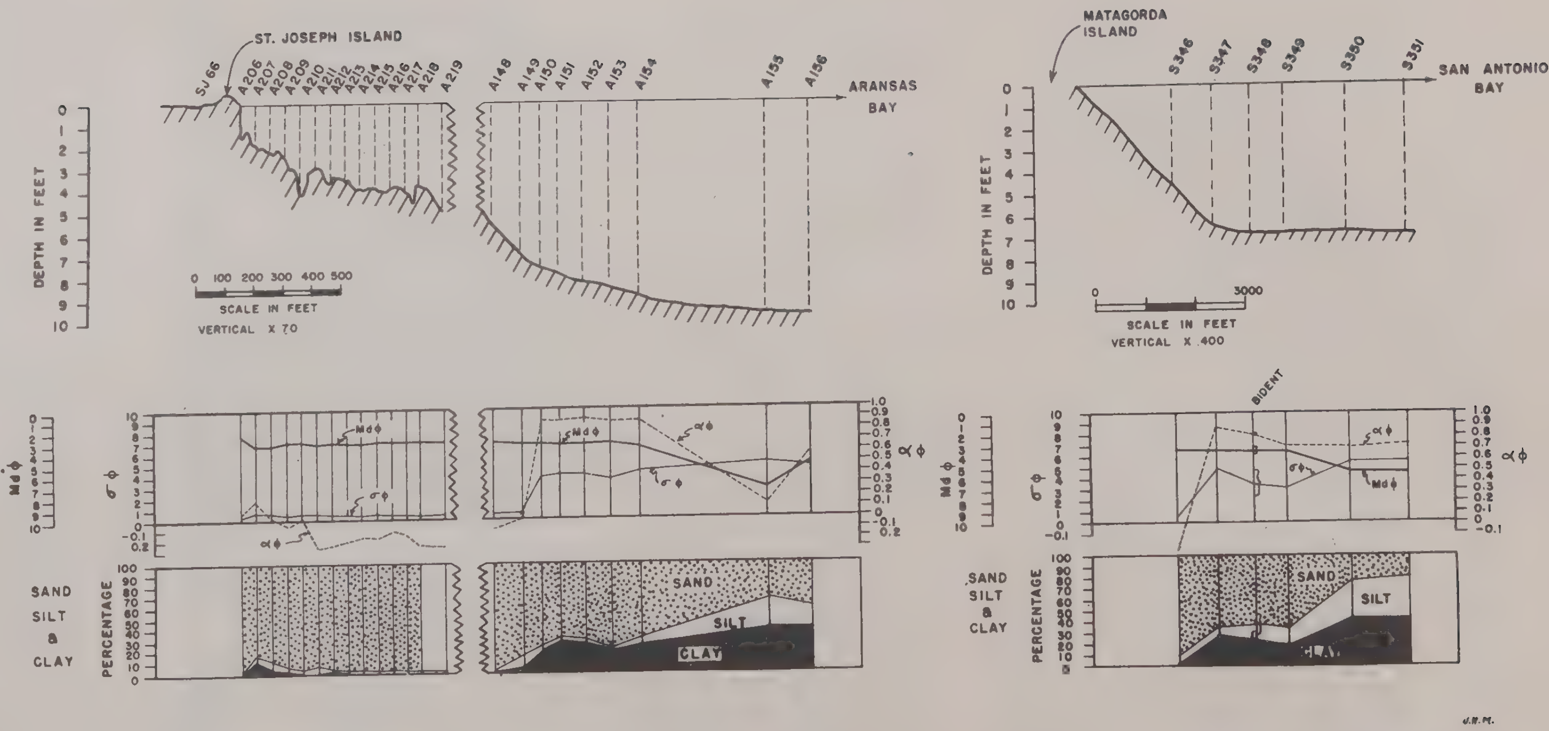


FIG. 47.—Variations in sediment parameters in closely spaced lines from barrier islands into bays. Sorting (σ_ϕ) and skewness (α_ϕ) change radically at base of slope, whereas median diameter (Md_ϕ) has little change at this point. Clay content increases before silt content with distance away from island.

from Laguna Madre appear to be rather similar to those of Redfish Bay as might be expected since most of Laguna Madre is also very shallow and even more saline than Redfish Bay. Furthermore, excepting in the southern end, Laguna Madre, like Redfish Bay, lacks entering streams.

Bays near rivers.—Another environment which is in a sense marginal to the bays is found in Mission Lake in Guadalupe Bay, and in a part of upper San Antonio Bay. This area is all relatively shallow but differs from "shallow bays" in having the influence of the fresh water and sediment coming in from the Guadalupe River. The sediments have several striking characteristics which differentiate them from those of the other areas. Lamination and stratification are commonly found in cores (Fig. 48). The sediments contain a fair abundance of wood fragments, of terrigenous or calcareous aggregates, and of ostracods. The ostracods and aggregates are most abundant in Mission Bay, which is rather distinct from the rest of this environment. A higher percentage of ostracods occurs here than in any known locality on the Gulf coast and the ostracods are considerably more abundant here than Foraminifera, an exceptional feature in sediments. The ostracods, the mollusks, and the Foraminifera are all very distinctive due to the low salinity.

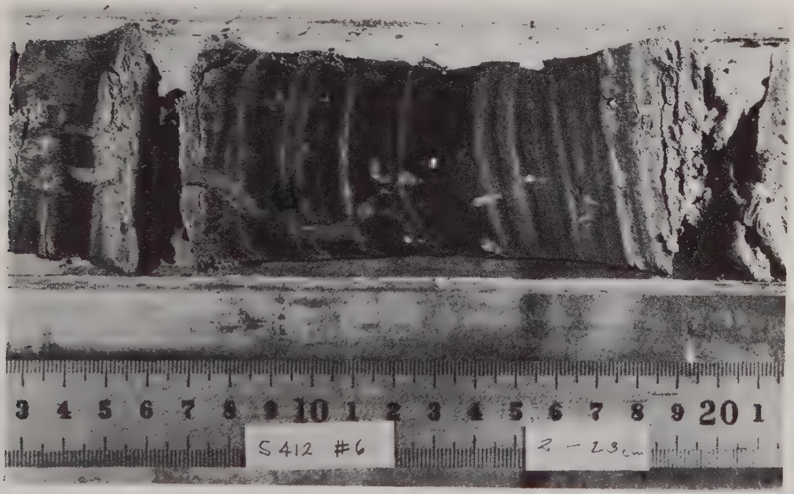


FIG. 48.—Typical lamination found in core in bay sediments near river mouths.

As in other nearshore environments the terrigenous minerals constitute the bulk of the coarse fraction. Of the fine fraction, clay greatly exceeds silt. This is even true in some samples along the margin of the bays adjacent to the low delta surfaces. On the other hand, locally a very narrow fringe of sand is found adjacent to the delta, extending out only a few feet from the shore. The silt and clay have high percentages of calcium carbonate, averaging 24 per cent, which is higher than in any environment excepting the delta.

Bays intermediate type.—This environment is found predominantly in San Antonio Bay and extends down the west side of the bay beyond the "bay near rivers" environment. The environment is intermediate between that of the low salinity of the upper bays and of the high salinity of the lower bays. The relation of sand, silt, and clay is similar to that found in "bays near rivers," the sediments being predominantly silty clays. The lamination found near river mouths is entirely missing. A marked difference is found in the numbers of Foraminifera which are more than three times as abundant as in "bays near rivers." Wood fibers and aggregates have virtually disappeared in this environment and only small numbers of ostracods are found. The clay minerals contrast with those of the "bays near rivers" environment, having far less montmorillonite and more illite and chlorite.

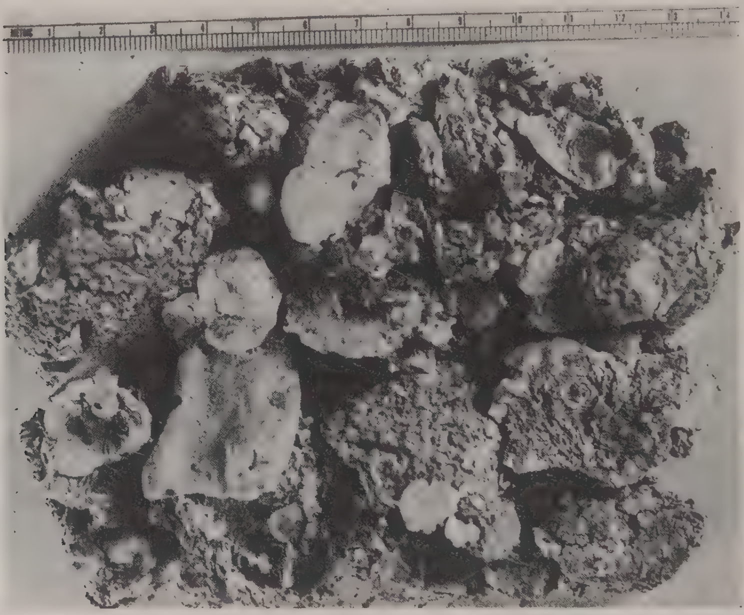


FIG. 49.—Photograph of oyster-reef débris obtained in boring operation in San Antonio Bay.

Oyster reefs.—Prior to the writers' boring operations in San Antonio Bay there was no material available to them which would allow an evaluation of the sediments in the oyster-reef environment, largely because the reef growth has been greatly retarded by intensive oystering. Washing by the waves has concentrated the shells at the surface of many reefs. These shell masses were difficult to penetrate to obtain normal reef sediments so that the only picture of the general constitution of the sediments in the oyster-reef environment has come from the borings in San Antonio Bay which passed through a maximum of 48 feet of nearly continuous oyster reef (Figs. 49, 57). The sediment of these reefs differs sharply from all other deposits in the area, being made up predominantly of broken oyster shells. Due to the size of the fragments, about 80 per cent of the coarse fraction is greater than a millimeter in diameter. In the fines, clay is more abundant than silt, averaging about 25 per cent in contrast to about 12 per cent silt. The shells are very largely oysters although they include associated forms, some of which are predators of the oysters. This is the only environment in which the percentage of terrigenous minerals averages well below the organic constituents. The environment is also particularly low in Foraminifera compared with other central bay environments. Sponge spicules are common, whereas they are rare elsewhere in the bays.

Bays near oyster reefs.—This environment is not well known in the Rockport area, being based largely on a series of samples which were taken in Copano Bay where the sediment may have been disturbed by shell dredging and oil-well drilling operations. In the Copano Bay samples, oyster shells along with a few shells of other forms constitute the bulk of the coarse fraction. Silt and clay, about evenly divided, form a much larger percentage than in the oyster reefs. The "bays near oyster reef" environment apparently grades into the other bay zones. The type does not extend far from the reefs in San Antonio Bay in spite of the fact that there are rather extensive reefs in that bay.

Bays no special influence.—This environment, which is practically confined to the relatively deep Aransas Bay southwest of Halfmoon and Long reefs, might better have been called the "deep bay" environment except that there is no evidence as yet to indicate that it is the depth which produces the special characteristics of the sediment. The samples are very low in sand and high in clay but also have a large amount of silt, higher than in most other bay zones. It is notable that this silt increases toward the center of the bay as shown in Figure 47. The gradation of sediment character from the "bay marginal" to the "bay no special influence" is shown in the same figure. The coarse fraction forms a striking contrast to the other environments. The Foraminifera constitute 33 per cent of the coarse fraction compared with 50 per cent terrigenous and 14 per cent shells. In many of the $\frac{1}{2}$–$\frac{1}{4}$-mm. and $\frac{1}{4}$–$\frac{1}{8}$-mm. sievings Foraminifera, mostly *Rotalia beccarii* and *Elphidium gunteri*, make up almost the entire sample. Comparison of the percentages in these sizes with other environments (Fig. 34) shows that all "bay no special influence" samples have more Foraminifera in these size ranges than all other bay samples analyzed.

Bays near narrows.—This environment is found either near an inlet coming in from the open Gulf or near a narrow strait leading to another bay. Mesquite Bay seems to be the type example of this particular environment, but it is also represented in a part of the southeast side of San Antonio Bay and in parts of northeast and southwest Aransas Bay. All of these areas are somewhat shoaler than the average depth of the bays. The characteristics of the environment include a dominance of sand and a higher percentage of clay than silt so that the sediment is principally a clayey sand. In some places the silt content is very much lower than the clay.

The bay areas with the highest sand, Mesquite Bay and lower Aransas Bay including part of the cove behind Mud Island, are near inlets leading into the open Gulf, which suggests that these inlets are an important source of the sand. Indicative of Gulf influence also are small quantities of echinoids which are rare in the other bay environments. The Foraminifera remain relatively high in percentage of the coarse fraction although not as high as in the deeper parts of the bays. The faunas are influenced by the introduction of material from the open Gulf. This is somewhat surprising in the case of the faunas of southeast San Antonio Bay because the connection to the Gulf is indirect, coming from Pass Cavallo and hence through 14 miles of Espiritu Santo Bay. Evidently under some northerly wind conditions, material must be introduced into the bay from this direction. The sand-silt-clay triangle diagram for this environment (Fig. 26) is very striking, showing a close grouping of most of the points in clayey sand.

BARRIER ISLAND ENVIRONMENTS

Barrier flats.—In discussing the barrier island environments it seems advisable to begin with the low swampy areas adjoining the bays which are partly submerged and include intricate channels and ponds (Figs. 7–10). In some places these barrier flats are fringed by narrow beaches which are predominantly sand with local abundance of shells which may be partly reworked from older deposits. Most of the flat surfaces are somewhat muddy, having about 30 per cent of silt and clay rather evenly divided. The coarse fraction shows that aggregates are rather common, which may be the result of alternate wet and dry conditions on the flat. When the water recedes, evaporation takes place and capillarity brings water to the surface, causing some cementation of grains largely with calcium carbonate and salt. Calcium carbonate cement is preserved, but the salt is redissolved when more water spreads over the flats. Wood fibers are more abundant than in any of the bay environments excepting that near the river mouths. Small amounts of echinoid plates and spines appear in the sediment apparently due to the overwash from the offshore areas. Because of the large sand content of these barrier flat sediments, terrigenous minerals constitute a higher percentage of the deposit than in any of the bay environments. A distinctive marsh facies of Foraminifera is found in most of the samples.

Inlets.—Near Rockport the inlets constitute only a very small part of the total area of the barrier islands although a rather large natural inlet, Pass Cavallo, is found just northeast of Matagorda Island. The samples from this inlet have been included in obtaining averages for the environment. This was necessary because Aransas Pass is maintained artificially by jetties. Cedar Bayou, the entrance into Mesquite Bay, has also been subject to some minor dredging. The inlet environment may be far more important in barrier islands than is indicated by the present islands. During hurricanes many inlets are opened through the barrier islands (Fig. 4) and these are subsequently filled. Since the sediments that fill these gaps are inlet deposits, barrier island sediments may consist very largely of deposits formed in this environment.

The sediments of the inlets are somewhat inconsistent one with another so that the averages may not be very significant. In some places the inlet deposits are almost entirely sand and elsewhere silt and clay run up to 50 per cent or even more. High percentages of mollusk shells and echinoid fragments are found in some of the samples. The environment differs also from all of the bay environments in having small amounts of glauconite suggesting the connection to the open Gulf.

Both Foraminifera and shells are more abundant than in the sediments of the "barrier flats." The fauna is of special interest as it contains a mixture of Gulf and bay forms due to the movement of currents alternately in and out through the inlets. Probably the fauna is the best means of recognizing the environment although similar organisms might live in the bays or open Gulf near an inlet which would cause confusion in ancient inlet deposits.

The closing of an inlet takes place on the Gulf side, leaving a channel with only a connection with the bay. As deposition fills the channel severed from the Gulf, the sediments should take on characteristics somewhat similar to those of barrier flats and there would be only a restricted open Gulf fauna consisting of the organisms which survive the closing. It is apparent that inlet deposits are not yet well understood and their recognition in older sediments should be subject to some doubt. This is unfortunate because many of the samples obtained under the barrier islands appear to be more closely related to those of the inlet deposits than to other environments.

Dunes.—Dune sediments are in many ways similar to those of the beaches. They are fine, well sorted sands with only 1–2 per cent of silt and clay.[13] Percentages of sand greater than $\frac{1}{4}$ mm. are negligible in most samples. Shells are the only constituent other than terrigenous of any significance and they amount to about 0.5 per cent of the deposit. Plant fibers are found in some of the dune samples although they are not consistently present and constitute on the average only 0.06 per cent. Probably the best means of differentiating dune and beach environments is by the greater roundness of dune sand grains as is shown in discussing the beach environment.

Gulf beaches.—The sands of the broad beaches that front the Gulf are approximately as well sorted as the dunes although they maintain a somewhat greater percentage in the 1–$\frac{1}{2}$-mm. and $\frac{1}{2}$–$\frac{1}{4}$-mm. portions. Shells are more abundant than in the dunes and Foraminifera which are almost entirely absent in the dune sands are found in small percentages on the beaches. Echinoids are more abundant than in any of the bay environments but not as common as in the inlets. There are local shell concentrates on the beaches which would give these particular samples an entirely different appearance from that of the average beach deposit. Glauconite is present in small amounts in most of the beach samples.

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[13] Some samples obtained in borings in the area have characteristics suggesting dune origin but have up to about 10 per cent of silt and clay, perhaps due to sifting or washing down from overlying deposits.

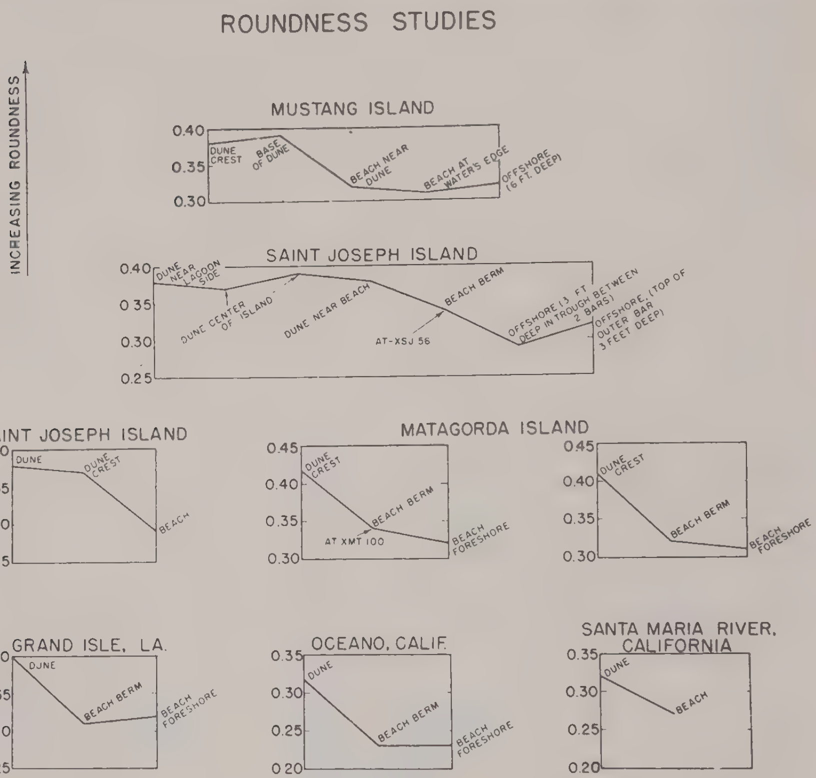

Fig. 50.—Variation in roundness in profiles extending from beaches to dunes. Roundness increases in all cores in dunes, but may be higher in dune near beach than farther inland. No horizontal scales indicated in this diagram (see also Fig. 30). Roundness values by M. A. Beal.

The roundness has been found to be greater in almost all dune sands than in adjacent beaches (Beal and Shepard, in press). Furthermore, in the central Texas area there is very little overlap between the two types (Fig. 30). Examples of the variation in roundness from beach across a wide dune belt are shown in Figure 50. It may be noted that the change in roundness occurs at the contact between the beach and the dune, and the roundness in the dune actually decreases slightly with increasing distance from the beach. Accordingly, it seems probable that roundness is the result of selective transportation due to the wind's picking up rounded grains from the beaches. This was well established in experiments by MacCarthy and Huddle (1938). Measurements of roundness at various depths below the surface of the dunes seem to show very little difference, indicating that the high percentage of rounded grains in the dune is not a lag concentrate at the surface. The bare possibility remains, however, that the concentration may develop successively as the dune is built higher and higher.

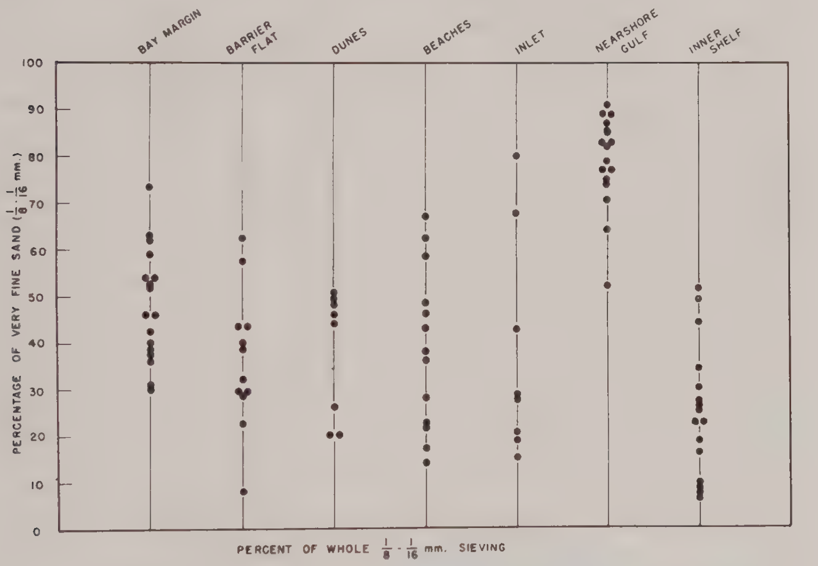

Fig. 51.—Percentages of very fine sand ($\frac{1}{8}$–$\frac{1}{16}$ mm.) related to sandy environments of Rockport area. Almost all nearshore Gulf samples have larger percentages than those of other environments.

CONTINENTAL SHELF ENVIRONMENTS

Nearshore Gulf.—A series of longshore bars and troughs which extend out for several hundred feet from the beach are essentially a part of the beach province. Outgrowth connects some of the bars to the beach during periods of small waves. Beyond this irregular zone and out to depths of a little more than 20 feet the slope has a greater inclination than elsewhere on the continental shelf. The "nearshore Gulf" environment extends down this relatively steep slope, the outer limit of which is apparently the outer limit of the breaking waves, except in rare hurricanes when waves may break at somewhat greater depths. The sediment of this environment is characterized by a sand content which averages about 91 per cent with a gradual decrease toward the base of the slope. Glauconite constitutes 0.25 per cent and echinoids 0.18, not very different from the adjacent beaches. Both shells and Foraminifera are scarce, distinctly less abundant than in the beaches. A marked contrast between the "nearshore Gulf" sands and both the beaches and dunes is the concentration of the sand fraction of the "nearshore Gulf" in the $\frac{1}{8}$–$\frac{1}{16}$-mm. size (Fig. 51), whereas in both the dunes and beaches the $\frac{1}{4}$–$\frac{1}{8}$-mm. size is slightly more abundant. Since there are very few exceptions to this rule it may provide a fairly satisfactory criterion for differentiating the two environments. The study of the roundness of the sand in a few of the "nearshore

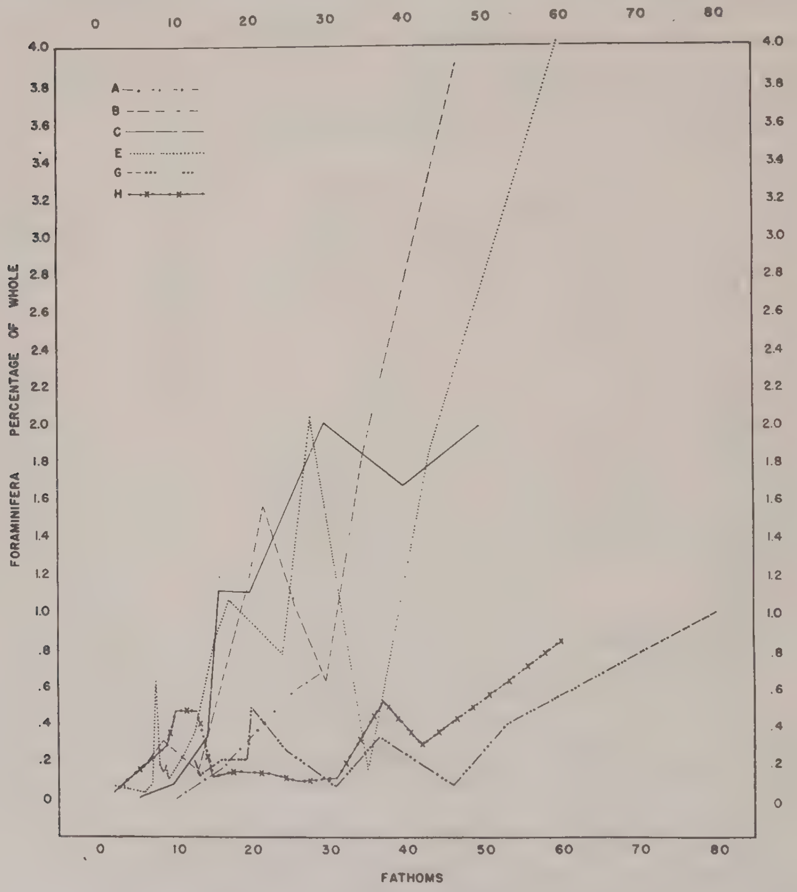

FIG. 52.—Variation in percentages of Foraminifera in samples with increasing depth. For locations of lines A to H, see Fig. 17.

Gulf" samples shows that they are less rounded than the beach sands and decidedly less rounded than the dune sands (Fig. 30). Thus there appears to be a progression between these three environments.

The fauna of the "nearshore Gulf" differs very little from that of the "Gulf beaches" since the beach sands include the Foraminifera and shells thrown up by the waves from the "nearshore Gulf." In both places the larger and especially the more substantial Foraminifera survive the pounding of the waves and constitute the chief element in the fauna. Many of the Foraminifera tests show the effect of wave abrasion.

Inner and outer shelf.—At least in the Rockport area there is no difficulty in differentiating between the "nearshore Gulf" and the "inner shelf" sediments, although in some places slight overlaps are found. The series of profiles showing the change in sand-silt-clay ratios going out across the shelf shows this marked break (Fig. 17). The inner shelf begins where there is a sharp fall-off in the sand content and a simultaneous growth of both the silt and clay content. The dividing line between the inner and outer shelf zones, however, is much less definite. An arbitrary line at 20 fathoms has been chosen, largely because this seemed to be the depth at which the greatest change in the Foraminifera takes place. Inside of the line the pelagic Foraminifera are very scarce, whereas outside of it they become abundant and constitute the majority of the Foraminifera in most samples. It is also noticeable that the percentage of Foraminifera in the whole sample increases with depth of water, with a rather sharp increase at or near the 20-fathom curve (Fig. 52). The calcium carbonate in the fine fraction of a few shelf samples also indicates a difference between the inner and outer shelf. Most of the samples on the outer shelf have a higher calcium carbonate content than on the inner shelf, with a dividing line around 40 °/₀₀ between the two (Fig. 43). There is also reason for believing that montmorillonite may be more abundant on the outer shelf than on the inner shelf (Fig. 31). Glauconite, on the other hand, is distinctly less abundant on the outer shelf than on the inner shelf in the southern part of the shelf, although the break at 20 fathoms is not distinct in this connection.

Examination of the cores from the southern part of the shelf showed sand lenses in almost all of the cores from the inner shelf (Fig. 53), whereas outside of the 20-fathom line such lenses are very rare. The dividing line between the zones with and without sand lenses varies somewhat in the different lines. The average content of ostracods was found to be about ten times as high in the outer shelf sediments as in the inner shelf sediments. It may be, however, that this difference is not valid because the percentages are all very small and estimation is difficult. In the southern part of the shelf the clay content is distinctly higher on the outer shelf and the sand content distinctly lower than on the inner shelf. This distinction, however, does not apply to the northern lines, and even off Cedar Bayou there are several samples with sand about as high on the outer shelf as in many of the samples of the inner shelf.

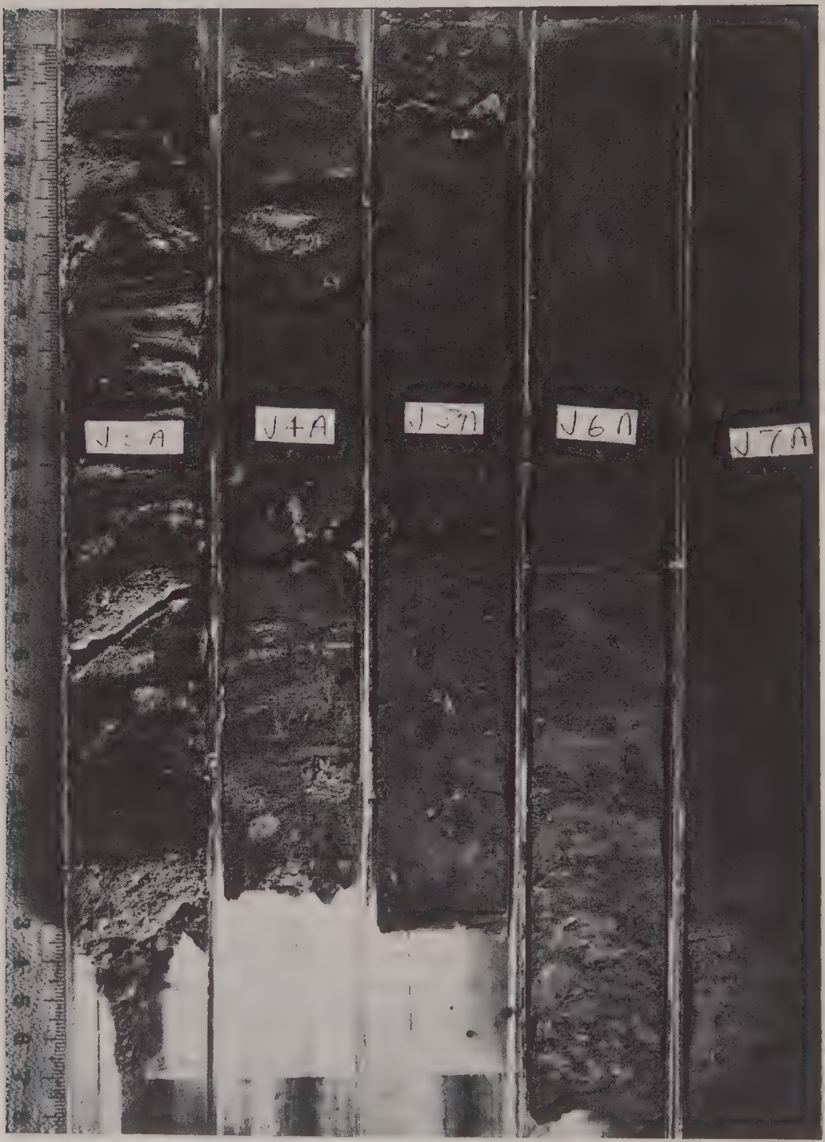

FIG. 53.—Typical sand lenses in nearshore part of inner-shelf cores Samples show increasing depth from J3A at 35 feet to J7A at 56 feet.

SUMMARY OF ENVIRONMENT CHARACTERISTICS

The preceding discussion has indicated that the sediments of each of the various bay, barrier island, and shelf environments of the central Texas area are subject to special influences which produce distinctive characteristics. Tests were applied to ten samples from these various environments with the locations withheld until after they had been diagnosed by various members of the project, each using different methods. The combined efforts of the team made it possible to identify the environment of all ten of the samples which were tested. By using the coarse-fraction analysis method alone a nearly perfect score was achieved. Both Foraminifera and ostracods were very effective in identifying environments as upper and lower bay or open Gulf. Macro-organisms were not well enough represented to use that method. The median-diameter, sorting, and skewness method was less successful in differentiating the environments of the unknown samples, and in a special test of the clay minerals only gross differences were observed. In other areas the relative importance of these various methods may be radically different.

In order to simplify the differentiating of environments in ancient sedimentary formations, it is best to use broader subdivisions and to pick out only the features which are most diagnostic. So far as one can júdge from the Rockport area, there are several characteristics of older formations which could serve to differentiate bay sediments from barrier island and open Gulf (continental shelf) sediments. Thus the faunas of the open Gulf and the bay sediments are certainly very distinctive and some of their characteristics may have held throughout much of geological time especially where ancient bays had a lower salinity than the open ocean. The shallow open Gulf is subject to occasional violent wave action in contrast to the protected bays so that this factor must also have an important effect on the faunas. Delicate shells which are ordinarily destroyed in the turbulent waters of the shallow open Gulf and beach environments may be preserved in the bays. One of the striking faunal differences which is most easy to recognize is the presence of oyster reefs in the bays and their general absence on the continental shelf. Oyster reefs do occur, however, in parts of the Gulf of Mexico that are near large river mouths where there is a reduction of the salinity.

Among the differences in physical characteristics of the three main environments can be included the greater abundance of silt in the open Gulf environments, especially in comparatively deep water at some distance away from the shoreline. Silt is for the most part rare in the bay sediments where the clay and sand constitute the principal constituents. On the other hand, calcium carbonate is commonly much higher in the bays. The glauconite of the open shelf sediments constitutes another major difference which may serve to differentiate Gulf from bay deposits. In a few places the glauconite has been carried into the bays through large inlets but no example of glauconite combined with echinoids has been found in the bays. Tests for differentiating bays from open shelf which are less positive but are worth considering include: (1) the percentage of $CaCO_3$ which is higher in most bay samples than in the open Gulf, the chief exception being in bays near inlets and on the outermost shelf (Figs. 41, 43); (2) the ratio of the percentages of Foraminifera in the $\frac{1}{2}$–$\frac{1}{4}$-mm. to the $\frac{1}{4}$–$\frac{1}{8}$-mm. sizes, and the ratio of the percentages of the $\frac{1}{4}$–$\frac{1}{8}$-mm. to the $\frac{1}{8}$–$\frac{1}{16}$-mm., a low ratio (less than 1.0) being more characteristic of the protected bays (Figs. 35, 36); and (3) the percentage of shells in the coarse fraction, 10 per cent or more being found mostly in the bays (Fig. 54).

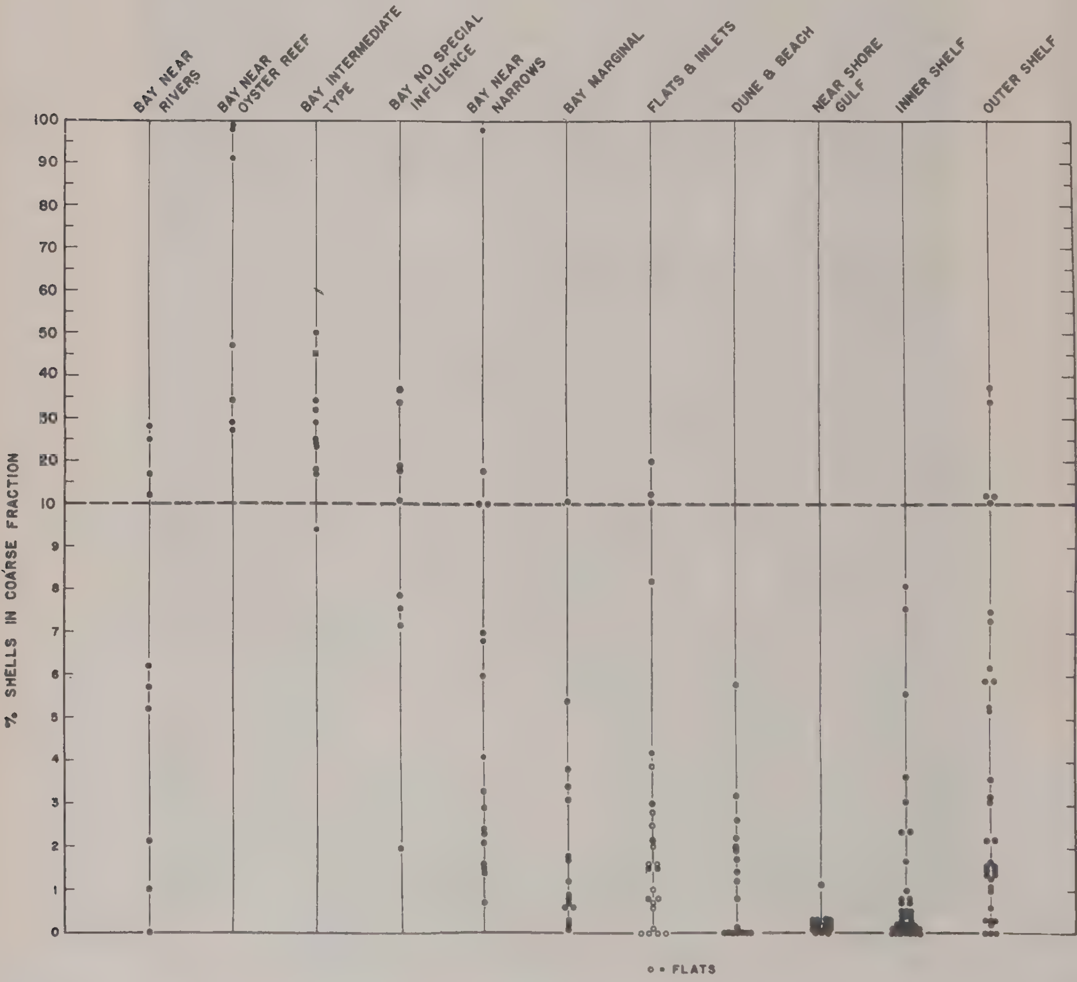

FIG. 54.—Percentage of shells in coarse fraction of samples related to environments. Shells are most abundant in central bays.

Barrier island deposits can usually be differentiated from those of the open Gulf and bays by their high content of sand. Sand, however, is also abundant in narrow belts near the barrier islands, both on the bay side and in the open Gulf. An examination of Figure 26 shows that almost all samples with 95 or more per cent of sand came from the islands or their margins. Similarly, most of the samples with more than 95 per cent terrigenous sands are related to the islands (Fig. 55). In some respects the barrier island sediments are transitional between the Gulf and the bays, both in characteristics of the heavy minerals and of the faunas. This is especially true where there are inlets which have allowed a back and forth movement of bay and Gulf materials.

Wherever pelagic Foraminifera are abundant a shelf environment is indicated. This abundance has not been found in the bays, or in the channels of the barrier islands, or in the inner shoal part of the continental shelf. Similarly, a great abundance of benthonic Foraminifera in the intermediate sizes of the coarse fraction of a sediment identifies a bay environment in the Rockport area (Fig. 34). Abundance of Miliolidae in the $\frac{1}{2}$–$\frac{1}{4}$-mm. size usually indicates a barrier island environment.

At least in the Rockport vicinity it appears to be possible to differentiate about 16 environments in the recent sediments. Thus the sediments deposited near the river mouths are the only bay sediments with lamination. Abundance of wood fibers, aggregates, and ostracods appear also to be good criteria to indicate nearness to river mouths. Many of these same characteristics are found also in the deltas which represent a transitional marine to fresh-water stage of deposition. The middle bays, where salinity is higher than at the river mouths, have yielded no lamination in the cores, evidently because of the abundance of organisms working over the bottom deposits. The middle bays are the zone where oyster reefs and oyster-shell débris are very abundant because of having an intermediate salinity which is especially favorable for *Crassostrea virginica* (the common reef oyster). Where lower-bay deposits are found near inlets, sand is abundant, very commonly constituting as much as 50 per cent. This sand is introduced through the inlets where the currents are strong. Where the lower bay deposits are formed at some distance from an inlet and where the water is comparatively deep, the sediments have a small coarse fraction in which Foraminifera are extremely abundant and terrigenous sand is exceptionally low.

The faunas show a steady progressive change down the bays, varying according to the increasing salinity in the direction of the open Gulf. Near the inlets the faunas show a mixing of bay and Gulf organisms. Similarly, the clay minerals reveal a decrease in montmorillonite with increase in salinity.

The barrier-island sediments are almost all high in sand content, in fact there is little else except where broad flats, channels, and lakes form the inner or bay side of northeast St. Joseph Island and Matagorda Island. In the $\frac{1}{2}$–$\frac{1}{4}$-mm. sievings Miliolidae are far more abundant than in bay or open Gulf samples. The beach and dune sands can be differentiated by the roundness coefficient which is higher in dunes than in any other environment. Also the beaches have more

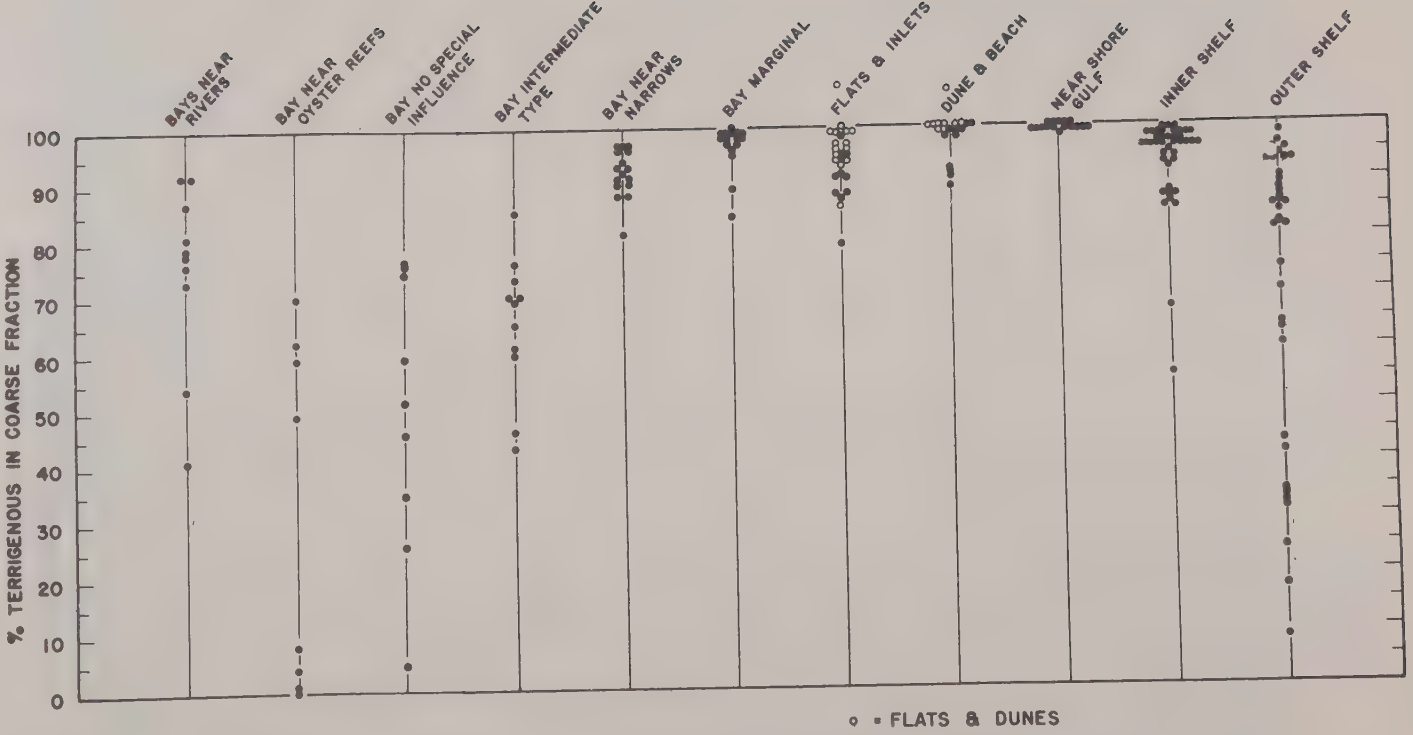

FIG. 55.—Percentage of terrigenous minerals in coarse fraction of the samples related to environments. Terrigenous minerals especially abundant in and near barrier islands.

coarse sand than the dunes and have more shell concentrates. Furthermore, glauconite is found in small quantity in the beaches and is almost negligible in the dunes.

The inlets and the barrier flats with their channels and circular lakes have a smaller quantity of sand, although in many places the sand constitutes more than 90 per cent of the whole sample. The inlet samples commonly have echinoid plates and spines which show open Gulf influence and the faunas in general include a mixture of Gulf and bay forms. Plant fibers are commonly washed into the inlet from the adjacent island. The barrier flats have a lower sand content than the other barrier island environments, and they have a considerable abundance of aggregates apparently due to an alternate wetting and drying of the areas in which deposition is occurring, with resulting precipitation of calcium carbonate and other evaporites around the mineral grains. In the barrier flat deposits plant fibers are also common, and pollens and spores are particularly abundant. This is true of both arborescent and non-arborescent types.

The sediments of the three continental shelf zones can be differentiated in most places. The nearshore Gulf, which includes the zones where waves are active and where the sand content is high (commonly more than 80 per cent), could be confused with some of the sediments of the barrier islands except that the overwhelming proportion of the sediment in the "nearshore Gulf" is found in the $\frac{1}{8}$–$\frac{1}{16}$-mm.-size fraction (Fig. 51), contrary to almost all of the sands on the barrier islands where it is more evenly divided in different size fractions. Also, the nearshore Gulf deposits can usually be differentiated from those of the barrier flats or inlets by having a considerable quantity of glauconite. Also, the faunas are far more typically open Gulf than they are on the barrier islands where there is commonly a mixture of bay, land, and open Gulf forms.

The inner-shelf sediments, extending out approximately to the 20-fathom curve, can be differentiated from the nearshore Gulf material by the far smaller quantity of sand and higher quantity of silt and clay on the inner shelf. Few bay samples have as much silt. Cores commonly show little pockets of sand of irregular shape. Apparently this is due to storms which carry sand out to the inner-shelf zone, forming layers which are later disrupted by the work of organisms. The inner-shelf sediments can be differentiated from those of the outer shelf by the scarcity of pelagic Foraminifera in the coarse fraction of the inner-shelf deposits and their abundance in the outer shell. A similar increase occurs in the micro-foraminifera in samples from the outer shelf and perhaps as a result there is a higher calcium carbonate content in the outer-shelf sediments. Off Rockport and Corpus Christi the outer shelf is very low in sand content and correspondingly high in clay. On the north, however, no such distinction is found in crossing the shelf.

THREE-DIMENSIONAL STUDIES

GENERAL

Most sediment units in old formations have a significant thickness. This third-dimensional aspect of the recent sediments in the Rockport area has now been investigated in several ways. Examination of the longest gravity and piston cores taken in the bays indicated slight changes of depositional conditions at depths of 3–4 feet below the core top. On the other hand, logs of cores made by engineers and by shot-hole drillers working in the area indicate that in most places the same general type of sediment persists for many feet below the surface, particularly on the barrier islands (Fig. 56). In order to learn the depths to which sediments representative of present conditions persist, a light portable drilling rig was obtained and 20 holes were drilled from a truck on the two barrier islands and in the Guadalupe Delta and from a barge in San Antonio and Aransas bays (Fig. 57A). These holes were carried down to an average depth of 55 feet and a maximum of 84 feet. In general the holes were alternately washed or bored for 3 feet and then cored for 2 feet. At two localities, however, continuous coring was conducted from depths of 25–35 feet. Elsewhere large intervals of washing or boring were

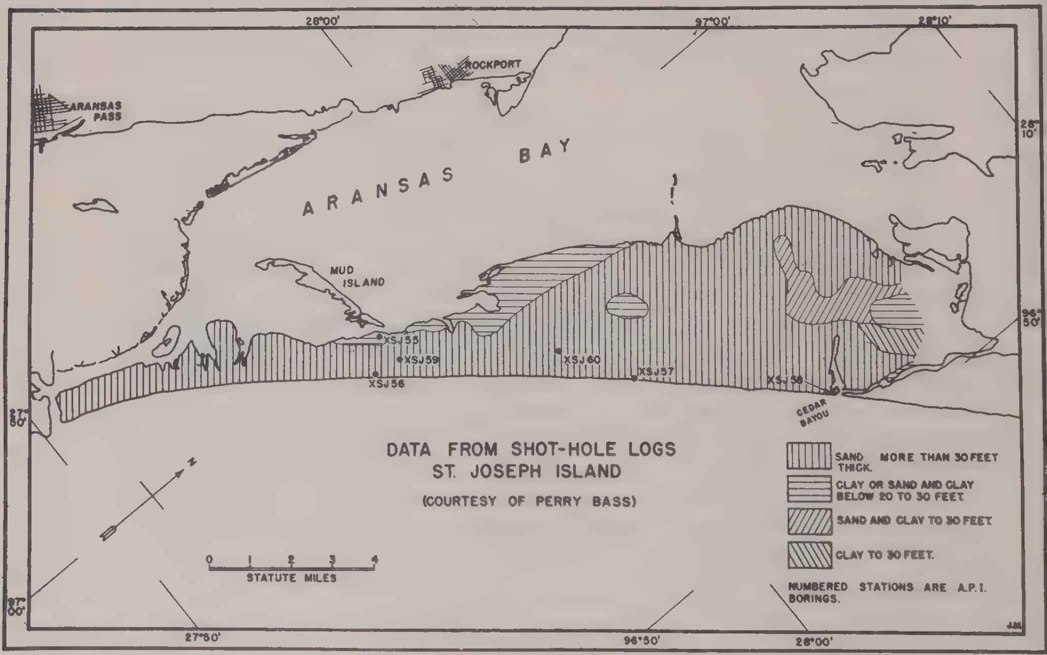
28°00'
97°00'
28°10'
ROCKPORT
ARANSAS PASS
ARANSAS BAY
MUD ISLAND
XSJ55
XSJ59
XSJ56
XSJ60
XSJ57
XSJ58
CEDAR BAYOU
28° 10'
96° 50'
27° 50'
97° 00'
DATA FROM SHOT-HOLE LOGS
ST. JOSEPH ISLAND
(COURTESY OF PERRY BASS)
N
0 1 2 3 4
STATUTE MILES
SAND MORE THAN 30 FEET THICK.
CLAY OR SAND AND CLAY BELOW 20 TO 30 FEET.
SAND AND CLAY TO 30 FEET.
CLAY TO 30 FEET.
NUMBERED STATIONS ARE A.P.I. BORINGS.
27°50'
96°50'
28°00'
J.M.

FIG. 56.—Data from about 100 shot-hole logs from St. Joseph Island. In most cores very considerable thickness of sand indicated. These well logs are substantiated by boring information.

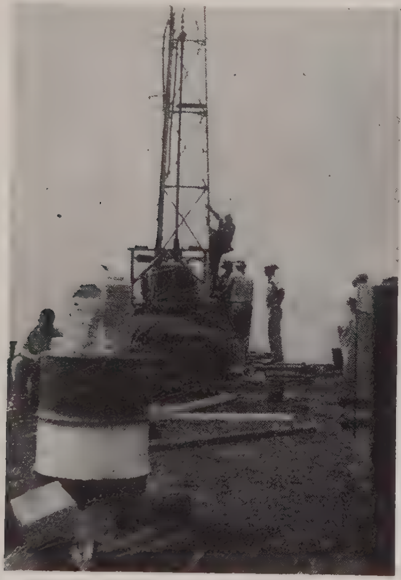

FIG. 57A.—Boring operation from barge on San Antonio Bay.

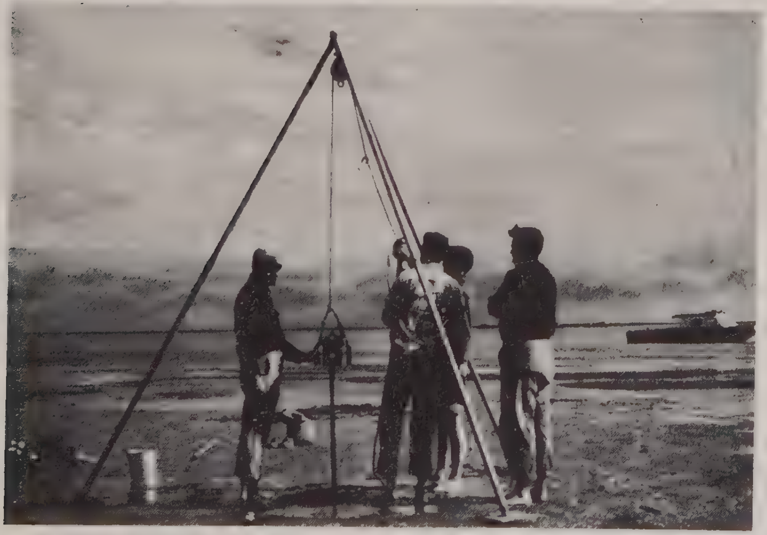

FIG. 57B.—Porter sampler operation on Mud Island.

made between coring operations either because of the uniformity of the material or because the bay operations had to be terminated at nightfall, and there was danger that the base of the Recent would not be reached. During all washing or boring operations, core cuttings were watched continuously.

Additional information was obtained by the use of a Porter soil sampler (Fig. 57B). This takes a one-inch core and can be pounded down to depths of about 40 feet. Ten holes were cored in this manner in the Rockport area. These go to an average depth of about 30 feet, approximately half of which is represented by actual cores. Two of these holes, however, were cored continuously to about 26 feet.

The borings give a fairly good coverage of San Antonio Bay and the delta at its head, and of the barrier islands (Fig. 58). However, no information was available concerning the continental shelf until the Humble Oil and Refining Company drilled in 42 feet of water south of the entrance to Cedar Bayou, between St. Joseph and Matagorda islands. Through the courtesy of Harold N. Fisk of Humble, samples of the sediments were obtained from depths down to 158 feet below the sea floor. Subsequently the Gulf Oil Company drilled 9 miles seaward of Padre Island at Corpus Christi and supplied cuttings of every 15 feet in the top 465 feet of the hole.

With all of this material it is possible to obtain a reasonably accurate history of depositional conditions in the area both during and since the rise of sea-level at the end of the last glacial epoch. In the description of cores that follows it may be helpful to refer to the section diagrams that show the sediment types of the traverse down San Antonio Bay (Fig. 59) and along the barrier islands (Fig. 60).

BORINGS IN GUADALUPE DELTA

The cores from three Porter soil-sampler holes and from two full-size borings have given a good coverage of the material underneath the Guadalupe Delta. Hole XG 18, which is farthest up the delta, about 8 miles from the distal end, passes through about 13 feet of material which is definitely deltaic in origin. Except for a silty sand around 8 feet it consists of a silty clay, rather high in ostracods and plant fibers, and has a large percentage of aggregates, and only a trace of Foraminifera. Portions of the cores show lamination. At about 18 feet the core changes into what appears to be a bay deposit although some of the shells and Foraminifera may be reworked. At 22 feet the sediment is yellowish brown, contains reworked material, and was apparently deposited during an earlier cycle, presumably the Beaumont stage of the Pleistocene.

The next hole, XG 17[14] which was located 2½ miles farther down the delta, has a smaller thickness of deltaic deposit than XG 18. At a depth of 9 feet a "bay near river" deposit was found. The change from delta to bay is represented by an increase in sand, a decrease in aggregates, and by the change in the Foraminifera, those found in the delta deposit having been reworked, whereas those

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[14] Used for chemistry; see Figure 72 and diagenesis discussion determinations.

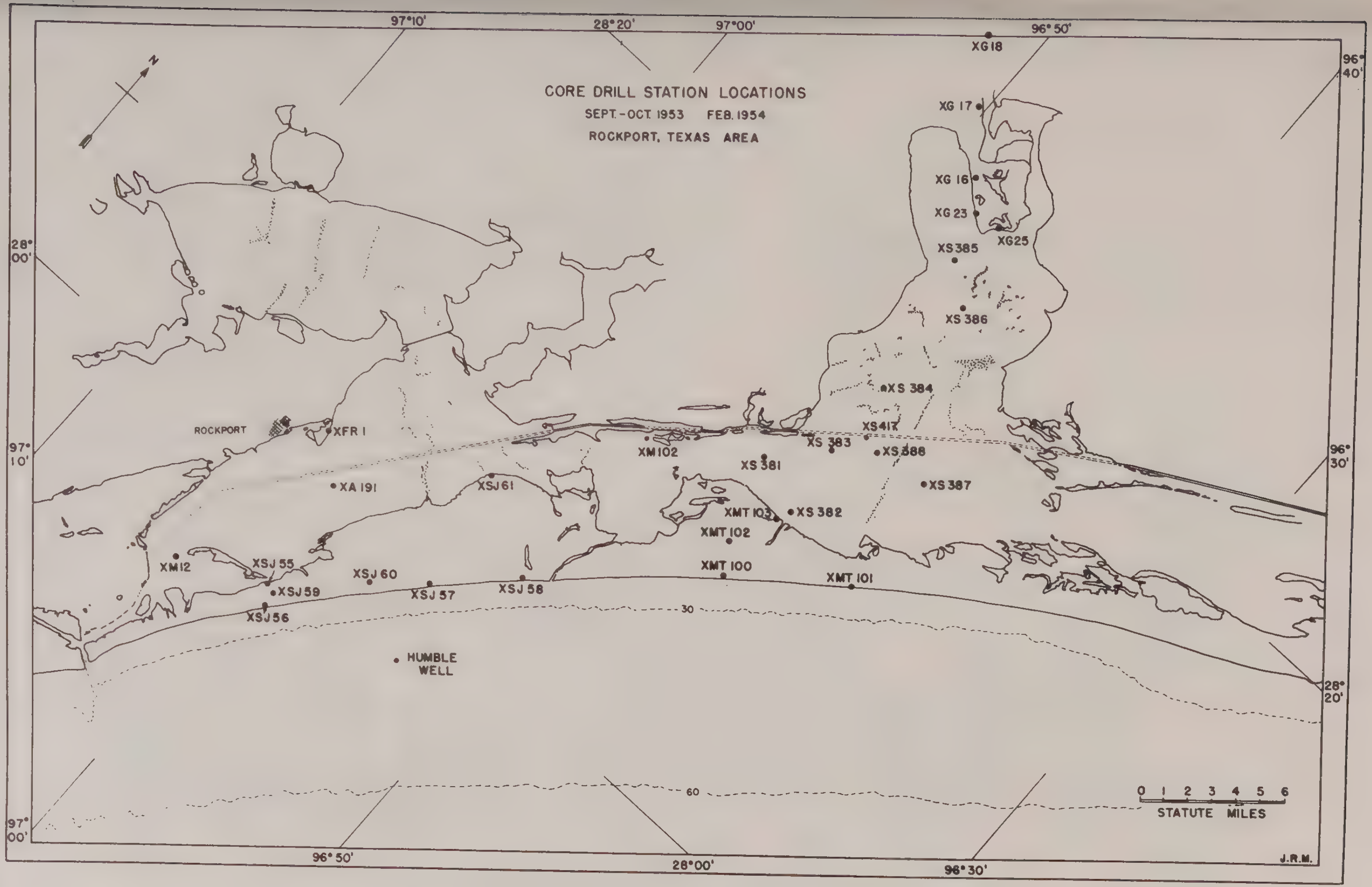
CORE DRILL STATION LOCATIONS
SEPT.-OCT. 1953 FEB. 1954
ROCKPORT, TEXAS AREA
N
97°10'
28°20'
97°00'
96°50'
96°40'
28°00'
97°10'
96°30'
28°20'
97°00'
96°50'
28°00'
96°30'
XG18
XG 17
XG 16
XG 23
XG25
XS385
XS 386
XS 384
XS417
XS 383
XS 388
XS 381
XS 387
XS 382
XMT 103
XMT 102
XMT 100
XMT 101
XM102
ROCKPORT
XFR 1
XA 191
XSJ61
XM12
XSJ 55
XSJ59
XSJ 56
XSJ 60
XSJ 57
XSJ 58
HUMBLE WELL
30
60
0 1 2 3 4 5 6
STATUTE MILES
J.R.M.

FIG. 58.—Location of borings in Rockport area.

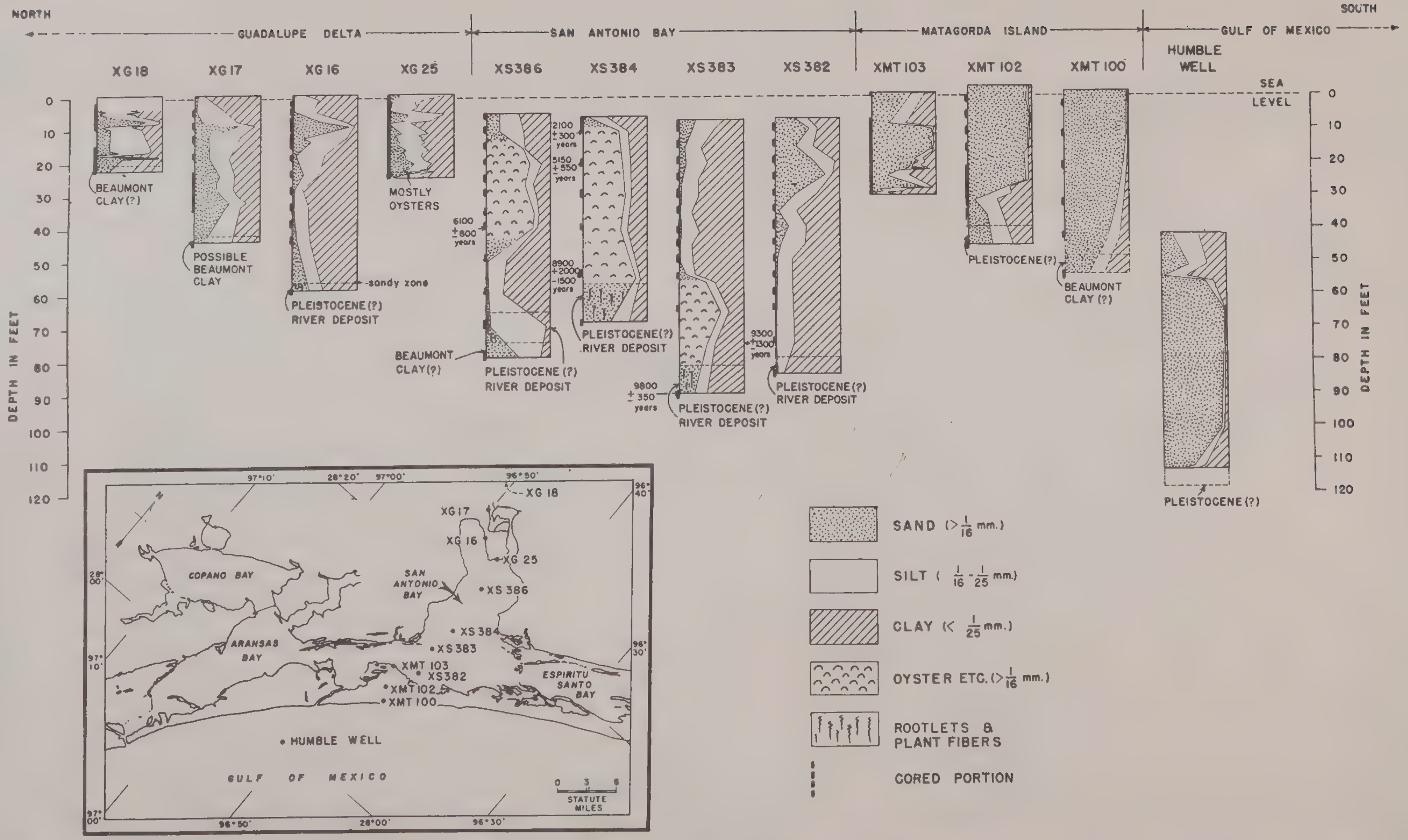
NORTH
SOUTH
GUADALUPE DELTA
SAN ANTONIO BAY
MATAGORDA ISLAND
GULF OF MEXICO
XG18
XG17
XG16
XG25
XS386
XS384
XS383
XS382
XMT103
XMT102
XMT100
HUMBLE WELL
SEA LEVEL
DEPTH IN FEET
0
10
20
30
40
50
60
70
80
90
100
110
120
BEAUMONT CLAY(?)
POSSIBLE BEAUMONT CLAY
sandy zone
PLEISTOCENE(?) RIVER DEPOSIT
MOSTLY OYSTERS
6100 ±800 years
2100 ±300 years
5150 ±550 years
8900 +2000 -1500 years
BEAUMONT CLAY(?)
PLEISTOCENE (?) RIVER DEPOSIT
PLEISTOCENE(?) RIVER DEPOSIT
9800 ±350 years
PLEISTOCENE (?) RIVER DEPOSIT
9300 ±1300 years
PLEISTOCENE (?) RIVER DEPOSIT
PLEISTOCENE(?)
BEAUMONT CLAY (?)
PLEISTOCENE (?)
SAND (>1/16 mm.)
SILT (1/16-1/25 mm.)
CLAY (<1/25 mm.)
OYSTER ETC. (>1/16 mm.)
ROOTLETS & PLANT FIBERS
CORED PORTION
97°10'
28°20'
97°00'
96°50'
96°40'
28°00'
97°10'
96°30'
97°00'
96°50'
28°00'
96°30'
XG 18
XG17
XG 16
XG 25
XS 386
XS 384
XS 383
XMT 103
XS382
XMT102
XMT 100
COPANO BAY
SAN ANTONIO BAY
ARANSAS BAY
ESPIRITU SANTO BAY
HUMBLE WELL
GULF OF MEXICO
0 3 6
STATUTE MILES

FIG. 59.—North-south section showing sand-silt-clay contents of samples from borings. Coarse fraction of oyster reefs shown by special symbol. Age determinations supplied by Magnolia Petroleum Company are included. Apparent flood deposit shown at about 10 feet in each boring in Guadalupe Delta. For environment interpretations see Fig. 68A.

below 9 feet comprise a true bay assemblage. The sand-silt-clay ratios suggest a correlation with the 8-foot zone in XG 18 (Fig. 58). Lamination was found in the silty clay zone between 12 and 14 feet, which recalls the lamination in some of the recent sediments of Guadalupe Bay. The sediments at about 19 feet which lack near-river characteristics suggest that the river may have entered at some distance from the site at that time. The organisms are like those found in the middle San Antonio Bay at present. Furthermore, from about 15–35 feet the sand, silt, and clay are of about equal abundance, and this is not indicative of the present-day "bay near river" deposits which are largely silty clay. The high calcium carbonate content at 13 feet suggests "bay near river" deposition but at 32 feet mid-bay carbonate contents were found. The color of the sediment changes at 43½ feet and becomes stiff, greenish, silty clay with some streaks of white clay and calcareous concentrations. This appears to be a weathered deposit of Pleistocene origin, probably Beaumont clay.

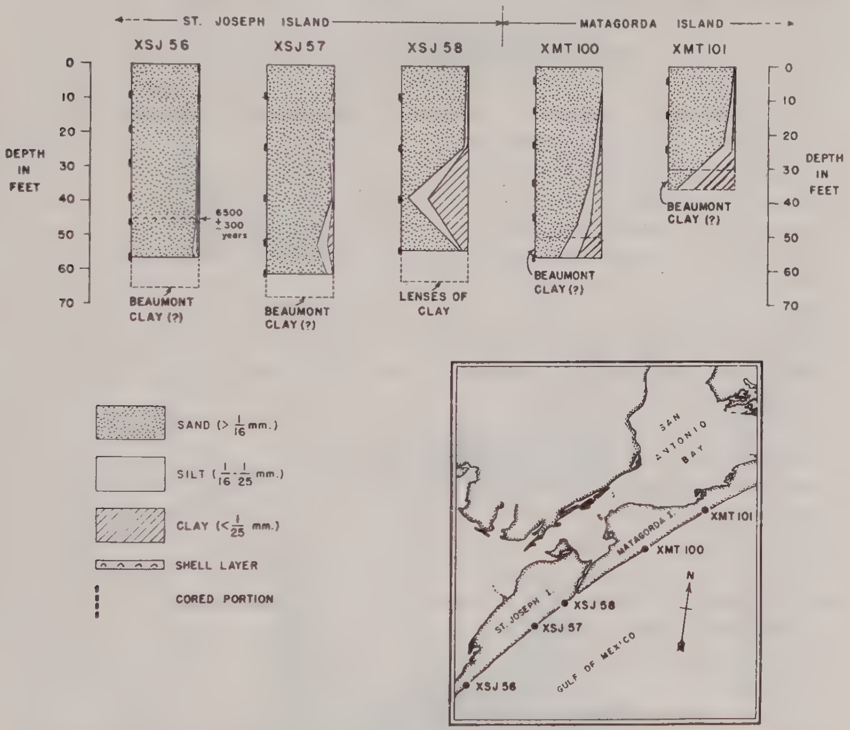
ST. JOSEPH ISLAND
MATAGORDA ISLAND
XSJ 56
XSJ 57
XSJ 58
XMT 100
XMT 101
DEPTH IN FEET
0
10
20
30
40
50
60
70
6500 ± 300 years
BEAUMONT CLAY (?)
LENSES OF CLAY
SAND (> 1/16 mm.)
SILT (1/16 - 1/25 mm.)
CLAY (< 1/25 mm.)
SHELL LAYER
CORED PORTION
SAN ANTONIO BAY
MATAGORDA I.
ST. JOSEPH I.
GULF OF MEXICO
N

FIG. 60.—Northeast-southwest section along barrier island beaches showing sand-silt-clay content in borings. Great thickness of sands and length of time involved in deposition (XSJ 56). For interpretations of depositional environment see Fig. 67B.

Hole XG 16 was located 3 miles farther down the delta. The cores from this hole have a sequence in the upper few feet which is similar to XG 17. The delta deposits at the top have abundant plant fibers and a very small coarse fraction, which has an abundance of reworked Foraminifera. At 8 feet, bay macro-organisms are found in addition to plant fibers, ostracods, aggregates, and a considerable amount of coarse terrigenous sand. This assemblage indicates a change to the "bay near river" environment. At 9.5 feet coarse sand is particularly conspicuous and the coarse fraction constitutes 86.8 per cent, which is far more than has been found in the present delta samples or in upper San Antonio Bay. This sandy sediment probably corresponds with the sands in XG 18 and 17 and may represent a flood deposit. At 13 feet the coarse sand has disappeared, and only 16 per cent of the material is found in the coarse fraction. At greater depths the bay sediments appear to have been deposited farther from the river mouth. The abundance of oyster shells in the coarse fraction at 24 feet may indicate nearness to an oyster reef. Also the Foraminifera are indicative of middle- or lower-bay conditions rather than upper. At 34 feet there is a significant amount of pyrite, mostly found in Foraminifera tests. Below the deltaic deposits in XG 16 the sand content is much lower than it is in XG 17, and clay is the predominant material. A river deposit with wood fibers was reached at a depth of 59 feet, presumably representing an older cycle.

Hole XG 23 made with the Porter sampler was located about a mile from the lower end of the delta. The cores go only to a depth of 17 feet. To a depth of at least 8 feet they contain sediment akin to that of the Guadalupe Delta or like the low-salinity deposits of Mission Lake. Below that there is a gap in the samples, and at 14 feet a deposit with plant fibers and bay Foraminifera indicates the "bays near river" environment. At 17 feet the plant material has disappeared and the deposit seems to be more indicative of central-bay conditions. There is a surprisingly low amount of terrigenous material, however, indicating an environment somewhat like that found in "bay no special influence" of the present Aransas Bay.

XG 25 was made also with the Porter sampler and was located at the very end of the Guadalupe Delta near Grassy Point. This boring is one of three made to date which were bored continuously from the surface to their greatest depths.[15] Actually, however, there are a few gaps in the samples because some of the 6-inch tubes came up empty, due to material being pushed aside during the pounding operation. Twenty-nine 6-inch samples were studied along the length of the hole. The results of this study (Fig. 61) provide the most detailed picture of the variation along the length of any of the borings. Several changes of environment are evident in the boring. These are best shown by the inverse relations of wood fibers and ostracods on the one hand with shell content on the other. The zones where wood fibers and ostracods are high near the surface are indicative either

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[15] One of these, not described here, was made recently in lower San Antonio Bay (Moore, 1955).

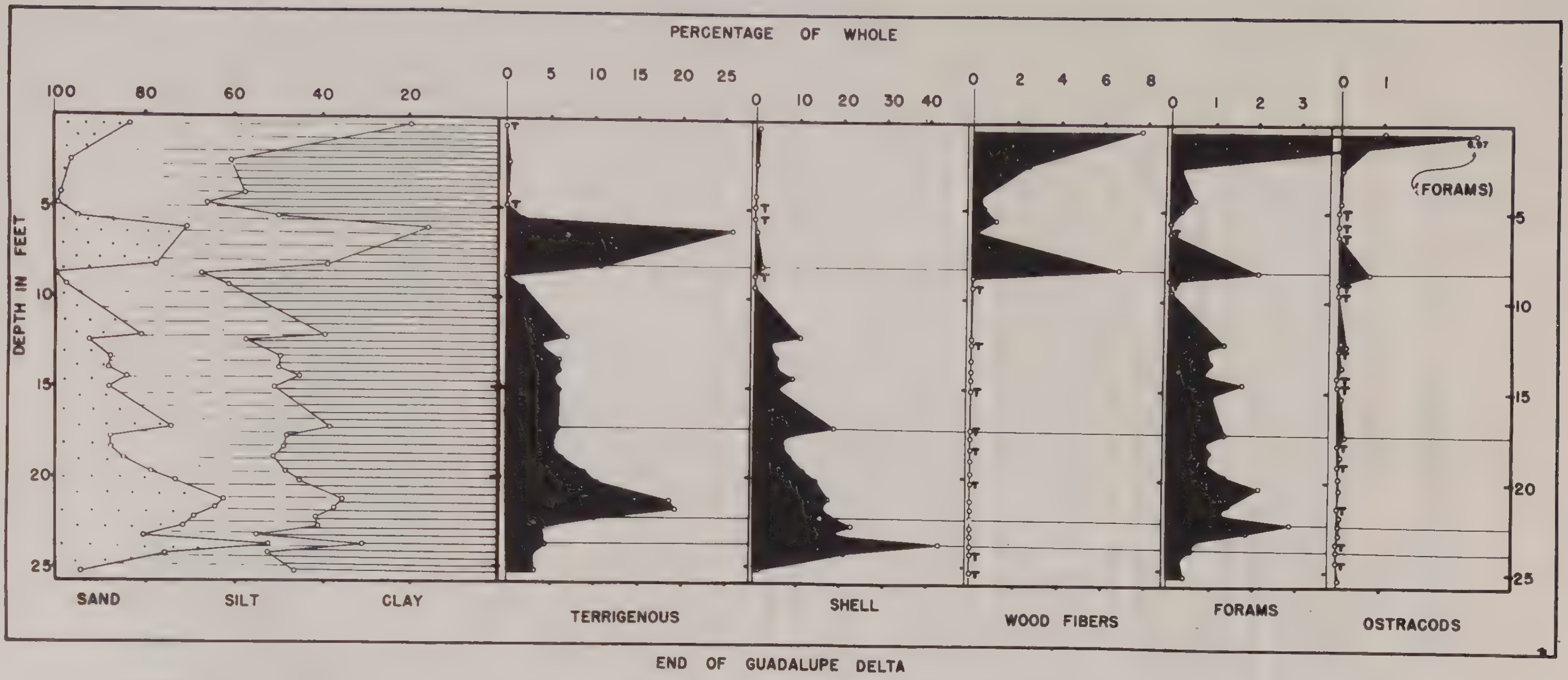

FIG. 61.—Variation in constituents in boring made at end of Guadalupe Delta. Symbol "T" indicates measurable percentage, but one which is less than 0.04. Excessively high percentage of Foraminifera in surface sample is indicated.

of nearness to rivers, or, more likely of actual delta deposition. On the other hand, the high shell contents found in the lower part of the hole indicate a central-bay environment and, since shells are almost entirely oysters, a nearness to oyster reefs. Thus there appears to be definite delta deposition at the surface and again in the zone from 6 to 8½ feet below the surface, whereas central-bay conditions are indicated from about 12 feet to the bottom of the hole. The 6–8½-foot zones appear to correspond with the "flood" stage indicated in the other delta deposits.

With these changing conditions in mind, it is interesting to see how some of the other constituents vary. The Foraminifera have many large changes in quantity along the length of the hole. At the surface in what is almost certainly delta deposition the Foraminifera reach the largest percentage of any sample studied. The fine parts of the coarse fraction here consist of about half Foraminifera and half plant fibers. Evidently the waves breaking on the exposed delta have been carrying up the wood fibers which are abundant in the water and also picking up the bay Foraminifera and throwing them over the end of the delta to build up this deposit. The Foraminifera have true bay characteristics which are not those of the marshes found just inside this particular locality. At greater depth in the hole the Foraminifera show a series of decreases and increases, reaching the second highest percentage at 22 feet below the surface. Here there is no appreciable amount of wood and the shells are fairly abundant. The terrigenous part of the coarse fraction is notably low along almost the entire length of the core, nowhere attaining more than 26 per cent of the whole and rarely more than 10 per cent. Even in the coarse fraction the terrigenous sand is nowhere more than 88 per cent and is commonly around 40 per cent, which is lower than any surface samples in the Rockport area, excepting those associated with oyster reefs and a few on the outer shelf (Figs. 27, 28, and 55).

The sand-silt-clay ratios are interesting in several respects. In the first place the silt content is high in most samples, much higher than is commonly found in bay deposits, although not exceptional for deposits near river mouths. From an examination of the sand-silt-clay content alone, it would be very difficult to tell much about the history of events, which is so clearly shown by the ratios of wood fibers and shells. Thus, from the sand content one might conclude that nearness to source of sediment was indicated with increasing depth in the hole because of the increase in sand content, but actually the sample with the highest sand must have been deposited right on the shore and the parts with high sand content near the bottom of the hole are high because of the sand-size shell fragments. Neither the median diameters of the samples nor the sorting give much indication of environment of deposition. For the most part the sorting is very poor because of the variety of materials introduced, such as the wood fibers and the shells which have little relation to the nearness to shoreline or effect of waves. Thus, the entire study of this particular series of samples indicates the great importance of knowing percentages of the principal constituents in the coarse fraction.

BORINGS IN BAYS

A hole was drilled at the entrance to Hynes Bay, XS 385, but only one core was obtained above what appears to be the Pleistocene Beaumont clay. The sample between 6½ and 7 feet has 59 per cent sand, which is much higher than at the surface in this location. The macro-organisms are suggestive of lower-bay conditions and the sediment is similar to that found in "bays near narrows." The core at 11–13 feet has the yellowish brown color and very stiff character suggestive of Beaumont clay and also contains an abundance of aggregates. Otherwise it is similar to many bay sediments.

The occurrence of Beaumont clay so near the surface in XS 385 suggested that the next hole be nearer the center of the bay. Therefore, XS 386[16] was located 3 miles below the delta and one mile below the northernmost oyster reefs of the bay. Shells are abundant in the first sample from 4 to 6 feet, although otherwise the general composition of the sample seems to be similar to "bay intermediate type" except that the 18.3 per cent of $CaCO_3$ found in the fine fraction is representative of upper-bay conditions. The next core, from 9 to 11 feet, encountered material of an oyster-reef environment. Shells constitute 96 per cent of the coarse fraction although clay is still abundant constituting 41 per cent of the whole sample. The same material persists except for a somewhat smaller content of silt and clay down to about 40 feet. In this oyster-reef zone the clay continues to dominate over the silt although the shell material of sand and gravel size is considerably greater than either the silt or clay. Only 1 or 2 per cent of the sand is terrigenous so that if the shells were removed the samples would be a silty clay. In the shell mass, along with the oysters, there is an abundance of bryozoa and various gastropods of a type which attacks the oysters. There are also worm tubes, and in some places sponge spicules are common. In places the shells have become pyritized. A Carbon-14 determination on the oyster shells from a depth of 35 feet showed an age of 6,100 ± 800 years.

At 43 feet a core was obtained which is clearly out of the oyster-reef environment. The material is silty clay and the coarse fraction, which amounts to only 1.6 per cent of the whole, resembles the "bay no special influence" environment especially in the great abundance of Foraminifera in the ¼–⅛-mm. fraction. The faunas are essentially mid-bay, but show some forms that might have come from the open Gulf. Foraminifera continue to be abundant in the sample between 53 and 55 feet. It is also notable that plant fibers form an appreciable part of the coarse fraction which may indicate the nearness of a river. On the other hand, it may be significant that calcium carbonate constitutes 12½ per cent of the fine fraction at 45 feet, which is comparable with present lower-bay conditions and is in contrast to the 41 per cent of calcium carbonate in the fine fraction which is found in the 5½–6-foot section. The best interpretation for the zone below the oyster reef is that it is an unmixed bay environment.

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[16] Used as chemistry core; see Figure 72.

Below a depth of about 60 feet the material in XS 386 changes apparently to an alluvial marsh deposit, as indicated by its scarcity of Foraminifera and its abundance of aggregates and plant fibers. Most of the coarse fraction consists of terrigenous minerals. Some fairly large wood fragments were obtained near the top of this section. The calcium carbonate of the 64-foot level is even higher than that at $5\frac{1}{2}$–6 feet. This also suggests close relation to the Guadalupe River. At 73–75 feet the material has a greenish tinge and is clearly subaerial in origin.

Four miles farther down San Antonio Bay another hole, XS 384, was drilled in the vicinity of present oyster reefs. Almost the entire boring penetrated reef material. Under 4 feet of silty clay the first sample, from $4\frac{1}{2}$ to 5 feet, has shells constituting more than 50 per cent of the entire sample and 97 per cent of the coarse fraction. These shells are principally oysters. Some of the deeper cores have even higher percentages of oyster shells. At 49 feet, there is only 0.06 per cent of material other than shells in the coarse fraction and the shells constitute 83 per cent of the entire sample. In this sample clay constitutes slightly more than 10 per cent so that here if the oyster shells were removed the residue would be silty clay. It is probable that the 45 feet or more of oyster-reef material in this boring is not absolutely continuous but it was difficult to obtain cores in this zone. To prevent loss of drilling fluid through the oyster-reef débris, the hole had to be cased continuously. As a result, progress was slow and only a few cores were taken during the drilling. Three Carbon-14 age determinations were made from the oyster-reef material. At 5 feet an age of $2{,}100 \pm 300$ years was obtained, at 15 feet $5{,}150 \pm 550$, and at 49 feet $8{,}900\left\{\begin{array}{l}+2{,}000\\ \\-1{,}500.\end{array}\right.$

The cuttings and the action of the bit indicated that at 51 feet the base of the oyster reef was reached, although the first core obtained below that was from 62 to 64 feet. Here the green-gray color and the hard, crumbly, sandy-clay material in which the coarse fraction is almost entirely terrigenous, is interpreted as Pleistocene and certainly not a bay environment. There were numerous rootlets running through parts of this core although these were evidently lost in wet sieving and did not show in the coarse-fraction examination.

Three miles lower down the bay five holes were bored along a line at right angles to the other section. These include XM 102, XS 381, XS 383, XS 388, and XS 387. The general character of this transverse section is shown in Figure 62. These borings indicate that what may have been a former river valley, with a depth of somewhat more than 80 feet, has been filled with Recent deposits. In XS 383, at a depth of 69 feet, an age by Carbon-14 of $9{,}300 \pm 1{,}300$ years was determined, so that the deposition presumably began during the time when glaciers were retreating and when the sea was still considerably lower than it is at present.

The deposits in the upper part of XS 381 and XS 383[17] are somewhat similar.

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[17] Used for chemistry core; see Figure 72.

Near the surface in these two borings the sediment is sand-silt-clay but at about 3–8 feet it becomes silty clay or clay and these fine sediments continue down to the Pleistocene in XS 381 and to 48 feet in XS 383 where an oyster reef is encountered. In appearance these silty clays were remarkably uniform (Fig. 63) except for a few inches of lamination at 44 feet in XS 381 where the material becomes locally sandy. The relatively high percentages of Foraminifera in the coarse fraction of the silty clays down to about 15 feet in XS 381 and down to 24 feet in XS 383 are suggestive of a deposit marginal between "bays no special influence" and "bay intermediate type." Both the Foraminifera and the macro-organisms indicate either undifferentiated bay or possibly lower-bay conditions.

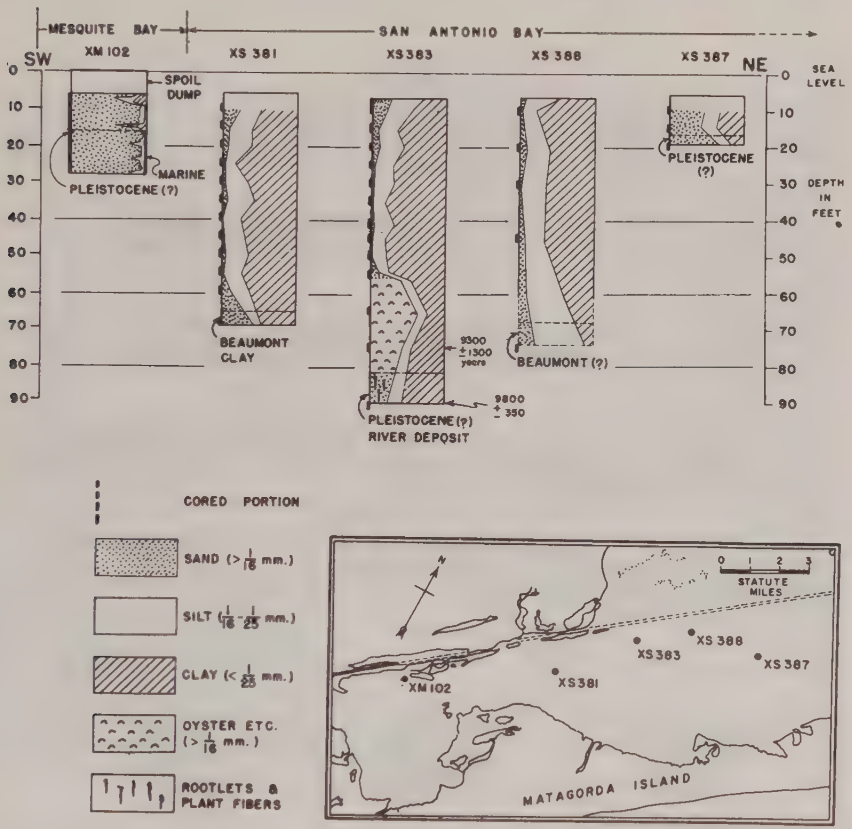
MESQUITE BAY
SAN ANTONIO BAY
SW
NE
XM 102
XS 381
XS 383
XS 388
XS 387
SPOIL DUMP
MARINE
PLEISTOCENE (?)
BEAUMONT CLAY
9300 ± 1300 years
9800 ± 350
PLEISTOCENE (?) RIVER DEPOSIT
BEAUMONT (?)
PLEISTOCENE (?)
SEA LEVEL
DEPTH IN FEET
0
10
20
30
40
50
60
70
80
90
CORED PORTION
SAND (> 1/16 mm.)
SILT (1/16 - 1/25 mm.)
CLAY (< 1/25 mm.)
OYSTER ETC. (> 1/16 mm.)
ROOTLETS & PLANT FIBERS
N
0 1 2 3
STATUTE MILES
MATAGORDA ISLAND

FIG. 62.—Northeast-southwest section of borings in lower San Antonio Bay, giving sand-silt-clay contents. Indication that Pleistocene river deposits in XS 383 were formed in center of Pleistocene valley.

The 14.9 per cent of calcium carbonate in the silt and clay in XS 383 at 19 feet is low compared with the present bay, being about comparable with the calcium carbonate of Mesquite Bay. At 44 feet in this same boring the 6.0 per cent of calcium carbonate is lower than in any of the near-surface deposits of the present bays.

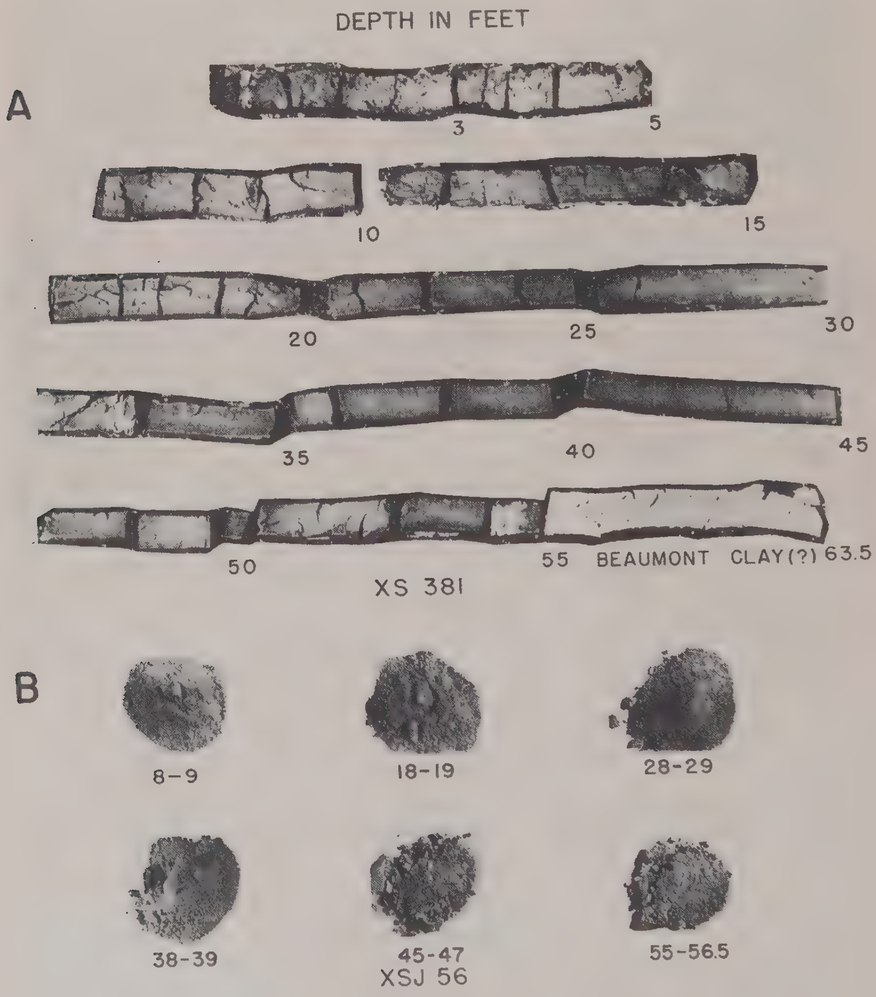
DEPTH IN FEET
A
3
5
10
15
20
25
30
35
40
45
50
55
BEAUMONT CLAY(?) 63.5
XS 381
B
8-9
18-19
28-29
38-39
45-47
55-56.5
XSJ 56

FIG. 63.—Core sections from boring XS-381. Note complete absence of stratification and change from bay clays to presumable Beaumont clay at 63 feet.

Where XS 383 changes into an oyster-reef environment at 48 feet, the contact was found in the core itself (Fig. 64). It is notable that in the oyster reef of this boring down to depths of 59 feet the shells constitute a smaller percentage of the coarse fraction than in the other oyster reefs. At 59 feet, however, the material resembles the oyster reef in XS 384 where the coarse fraction consists almost entirely of shells. The material at 43½–44 and 47½–48 feet looks like an oyster reef as far as the coarse fraction is concerned but there is a high percentage of silt and clay in both samples so that it is probably better to consider it as having been deposited in a "bay near oyster reef" environment. The true oyster reef is known only from 48 to 69 feet and the lowest sample at 68½–69 feet has only 42 per cent of shell material in the whole sample, the rest being largely clay.

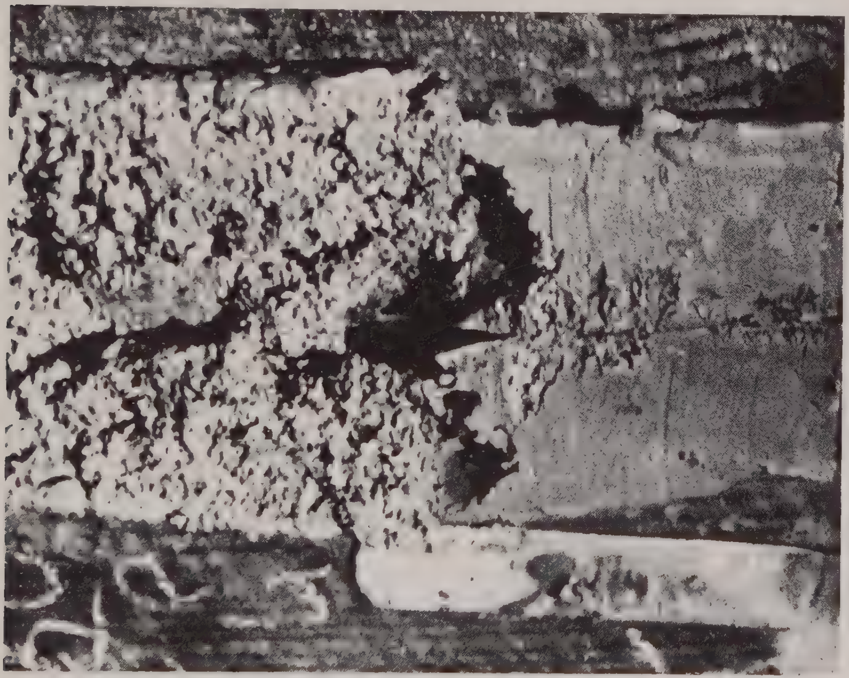

FIG. 64.—Contact between bay clay and oyster-reef zone observed at depth of 48 feet in XS 383.

A core at 83–85 feet in XS 383 revealed dark brown, crumbly, silty clay with abundant wood fragments of various sizes. It showed lamination in some places and has been interpreted as a river-bottom or fresh-water marsh deposit, clearly belonging to an earlier cycle. A Carbon-14 determination gives an age of 9,800 ± 350 years. In XS 381 presumed Beaumont clay was found at a depth of 63 feet.

The coarse fraction of this material is largely calcareous aggregates with some quartz in the finer sizes. It lacks shells and Foraminifera.

The cores from XS 388 on the northeast side of the former river valley are similar to those of XS 381 and, in the upper part, to XS 383. The material is predominantly silty-clay but somewhat sandier near the surface. The Foraminifera form a moderately important element in all samples to the base of the Recent. The coarse fraction resembles "bays intermediate type," or "bays no special influence." Beaumont clay or something similar to it was encountered at 67 feet in XS 388. The material of the latter is largely calcareous aggregates with a moderate amount of terrigenous sand but no shells or Foraminifera.

Hole XS 387, which was drilled in the sandier section of lower San Antonio Bay east of Panther Reef, penetrated to only about 13 feet before encountering presumed Beaumont clay. The two samples obtained above the Beaumont at 4–4½ and 8½–9 feet are similar to the "bay near narrows" environment of the present-day sediments. It is notable that a small amount of glauconite is found in both of these samples, suggesting a supply from an open Gulf source. Echinoids, however, do not appear. The sand content of 42–46 per cent is predominantly terrigenous, similar to that at the surface. The Beaumont has an abundance of aggregates and terrigenous material which compose the bulk of the coarse fraction. There are almost no shells, and no Foraminifera were found.

Hole XS 382 was located at the base of the bay slope near Matagorda Island and 3 miles south of XS 383. The effect of nearness to the barrier island was indicated in the upper part of the hole where three of the four cores have a sand content of more than 50 per cent and most of the sand is terrigenous. The environment is suggestive of "bay marginal" or "bay near narrows." At 9 feet, Foraminifera are very high, constituting 2.17 per cent of the whole. At a depth of 23 feet, the sand decreases to 31 per cent. Below 9 feet, the Foraminifera are abundant in some sieve sizes but do not constitute important percentages of the whole.[18] Pyrite is found in considerable abundance below 30 feet and glauconite occurs in small quantities mostly above 25 feet. The coarse fraction is very small in the deeper cores of the hole, indicating that during the deposition of these sediments the area was not near either a barrier island or an inlet. In this deeper part the deposits closely resemble the deeper cores of XS 381. In some places a "bay no special influence" environment is suggested by the foraminiferal abundance in the coarse fraction but the Foraminifera are not as numerous as in the present-day sediments of Aransas Bay. At 77 feet, the bay deposits come to an end and a river or fresh marsh deposit is encountered. The coarse fraction of this deposit is very high in wood fragments but it makes up less than 5 per cent of the total sample so that not as much total wood was obtained in this sample as in the bottom of XS 383.

One hole, XM 102, was in the northeast end of Mesquite Bay, next to Roddy

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[18] Studies of the variation in Foraminifera abundance are discussed in more detail in a subsequent section on Rates of Deposition.

Island, a little more than a mile from the old barrier island on Blackjack Peninsula. Sampling with the Porter sampler was continuous from the surface to 28 feet. It seemed likely that the top 6 feet were influenced by the spoil banks of the nearby intra-coastal canal. At greater depths a more normal sequence is encountered. However, only two samples particularly resemble the characteristic Mesquite Bay environment with its relatively high sand and clay content. These two are found between depths of 8 and 9 feet. Farther down, from 9 to 16 feet, the samples are indicative of a very shallow bay, such as Redfish Bay, judged by their macro-organisms and the high sand content. Beginning at 16 feet there are indications of slight weathering in the form of ferruginous aggregates and the samples are high in terrigenous sand and almost entirely lacking in Foraminifera and macro-organisms. Since they have a low roundness coefficient, a beach origin is suggested. At 20 feet the samples have acquired a considerable abundance of beach or surf-zone organisms, both in the Foraminifera and in the macro-organisms. The sand in the $\frac{1}{8}$–$\frac{1}{16}$-mm. size predominates in contrast to the samples higher in the hole and fits into the nearshore Gulf category, although there is an amazing scarcity of glauconite in contrast to the typical nearshore Gulf samples along the Texas coast. At about 24 feet the glauconite is found in small quantities, still much smaller than the typical Gulf samples of the present. The nearshore Gulf characteristic of high percentages in the $\frac{1}{8}$–$\frac{1}{16}$-mm. size continues to the bottom of the hole. The Foraminifera in the lower part appear to be open Gulf, with less indication of nearness to the beach than in the 19–24-foot zone. There is some decrease in the sand proportion below 19 feet which is also suggestive of deeper water. It seems likely that the boring in Mesquite Bay passed through the Recent at about 16 feet and into Pleistocene sediments which were deposited in the zone bordering the old Pleistocene barrier island of Blackjack Peninsula. The sequence also appears to indicate that this barrier island was encroaching onto nearshore Gulf deposits, unlike the outer part of the present barrier islands in the Rockport area. The presence of this Pleistocene marine deposit is attested by the macro-organisms, the Foraminifera, and the high percentages in the $\frac{1}{8}$–$\frac{1}{16}$-mm. size, although it is not confirmed by the glauconite, which is certainly much scarcer than in the present open Gulf sediments.

The only other boring in the Rockport bays was located near the center of Aransas Bay, hole XA 192. This boring apparently ended in bay deposits despite the 67-foot depth attained where it was necessary to stop. The samples vary considerably along the length of the hole. At $5\frac{1}{2}$–6 feet the high percentage of Foraminifera in the coarse fraction indicates the "bay no special influence" environment which is found also in the surface samples. At 10 feet the material has changed radically. The Foraminifera and the shells become a very small percentage of the sample. Glauconite, on the other hand, is surprisingly high, as much as 0.12 per cent of the whole, which is comparable with many of the open-Gulf samples although no echinoids were found and the macro-organisms and Foraminifera are suggestive of bay conditions. The sample has no exact counterpart in any of the recent bay samples studied, but is suggestive of a bay environment. At 15 feet the sand percentage decreases to 11.6. The silt has increased to 50.4 per cent, rather high if this represents a bay environment. The Foraminifera and macro-organisms are still very scarce and glauconite, although present, is less abundant than at 10 feet. The evidence from organisms is conflicting. The Foraminifera suggest a possible Gulf origin and the macro-organisms more of a bay environment. The possibility of its being near a bay entrance is unlikely because of the small percentage in the coarse fraction. This sample is therefore somewhat of an enigma.

The Foraminifera and shells continue to be abundant in the next two samples of XA 192 at 20 and 25 feet, and the coarse fraction is even smaller than those higher in the hole. The presence of aggregates suggests the possibility that the sediment is a land deposit. At 30 feet the sand fraction is slightly increased but otherwise the sample is similar to those found nearer the surface. Aggregates increase gradually until they constitute slightly more than one per cent at a depth of 34 feet, giving an indication of subaerial origin. At 38 feet shells become abundant again and there is an increase in the coarse fraction up to 69 per cent. Foraminifera also have increased considerably. The constituent percentages of the coarse fraction are rather suggestive of the "inlet" environment and this is supported by the organisms. At 44 feet the coarse fraction is increased to 85.6 per cent and Foraminifera have largely disappeared. The roundness is slightly lower than is ordinarily found in dunes. The sample most closely resembles material from the barrier island flats. At 57 feet the sand has been reduced to 37 per cent, Foraminifera have come back, and shells are abundant. The shells are a mixture of open Gulf and lower-bay types. A connection with the Gulf is also suggested by the presence of both glauconite and echinoids. At 66 feet there is another mixed fauna of Gulf and lower bay. The coarse fraction has 36 per cent, but glauconite and echinoids are both scarce, so that a more protected bay environment than at 57 feet is probable.

BORINGS IN BARRIER ISLANDS

Twelve borings were made on Matagorda, St. Joseph, and Mud islands, nine of them with the drilling rig and three with the Porter soil sampler. For convenience these may be divided into (1) those located in the present "barrier flat" environment of which there are four (2) those located in the middle of the island near the inside of the dune tracks (one actually on the dunes), and (3) a series of five along the outer Gulf beach.

On the bay side of the islands, XMT 103, a Porter sampler hole, was located in close proximity to the XS 382 in San Antonio Bay. The samples are nearly continuous from 8½ to 31½ feet. The first sample from 8½ to 9 feet, is representative of the "barrier flat" environment. It has a small coarse fraction (31 per cent) which is mostly terrigenous material but includes some plant fibers and shells. Below that to 10½ feet the cores show increasing amounts of terrigenous sand and

Foraminifera. The macro-organisms suggest an inlet deposit. At 10½ feet a sand deposit was encountered which continues with about 94 per cent sand content to a depth of 17 feet. The mixed faunas, the presence of rather abundant echinoids, the abundance of miliolids in the $\frac{1}{2}$–$\frac{1}{4}$-mm. size, the scarcity of glauconite, and the relatively small weight percentages in the $\frac{1}{8}$–$\frac{1}{16}$-mm. sizes are evidence for an inlet environment. Below 17 feet the sand content decreases and bay faunas increase, suggesting that the inlet may have had less access to the open Gulf. Plant fragments are found in samples at a depth of about 24 feet along with aggregates. Sand again increases to 90 per cent at 29 feet but this is underlain by much finer material beginning at 29½ feet where the coarse fraction drops to 13 per cent and clay dominates. The coarse fraction of this silty clay has an abundance of the kinds of Foraminifera which characterize the lower-bay environment. The next sample, at 30½–31 feet, is also mostly silt and clay. The Foraminifera are still very abundant and resemble those in the near-by bay borings at the same depth. Both pyrite and glauconite are found. The lowest sample from 31 to 31½ feet is the only one which is relatively low in Foraminifera, and it has an abundance of pyrite which may be largely a replacement of the Foraminifera. It has a coarse fraction of a little less than 10 per cent. All this material below 29½ feet appears to be a bay deposit. This hole did not enter the Pleistocene formations.

Hole XSJ 61, also by Porter sampler, was located at Jaybird Point on St. Joseph Island where an overwash fan appears to have built out onto the northeast part of Aransas Bay. The aerial photograph (Fig. 8) shows a series of channels crossing the island. These are connected to the open Gulf during high-water stages. It was thought, therefore, that cores would penetrate at shallow depth into bay deposits underlying this low overwash fan. The samples taken between 5 and 9 feet, however, are too low in both shells and Foraminifera to make it likely that they were deposited in bays. The sand content is about 90 per cent and almost entirely terrigenous. Only small amounts of echinoids are present and almost no glauconite. The samples somewhat resemble the sediment obtained from the flats along the north side of Matagorda Island. It seems likely that they were deposited in a barrier flat environment rather than in a bay or an inlet. The second group of cores was obtained from 19 to 24 feet. In all of this group the sand fraction is much smaller, averaging about 40 per cent, and Foraminifera are much more common. Small amounts of glauconite and echinoids are also found, but here also the coarse fraction is predominantly terrigenous minerals. The Foraminifera from two of the samples have a mixture of open-Gulf and lower-bay forms. The abundance of the Miliolidae observed in the $\frac{1}{2}$–$\frac{1}{4}$-mm. fraction is suggestive of a barrier island environment. It is concluded that these samples were an inlet deposit in a barrier island which had some access to open Gulf water.

The next suite of samples in XSJ 61 was from 29 to 33 feet. All of these samples have a high coarse fraction averaging about 85 per cent. Foraminifera are almost entirely absent and shells are very scarce except in the bottom sample where they constitute $2\frac{1}{2}$ per cent of the whole. No glauconite was observed and echinoids are extremely scarce. Two of the samples showed a few plant fibers and two others a small amount of aggregate. Almost the entire amount of each sample is found in the $\frac{1}{4}$–$\frac{1}{8}$- and $\frac{1}{8}$–$\frac{1}{16}$-mm. sizes. In one of the samples a roundness coefficient of 0.38 was obtained which is in the dune range for the area. If it were not for the relatively high silt and clay content a dune origin would seem most probable for all of this suite. Perhaps overwash carried in sand from a dune system. The absence of shells and Foraminifera may be explained by subsequent solution. The greenish color of part of the sand may be suggestive of an older Pleistocene formation although this color is not consistent throughout the length of the 29–33-foot cores. The formations are definitely not typical of either present-day bay or marine conditions.

One of the borings, XSJ 55, was located along the bay shore of St. Joseph Island near the east end of Mud Island. The samples from this hole showed a consistently high sand content and, unlike the sandy samples from XSJ 61, Foraminifera are well represented in almost all samples and shells, and echinoid fragments are abundant in many of them. Small amounts of glauconite are found in several samples and aggregates occur in two. It is notable that the Foraminifera in the $\frac{1}{2}$–$\frac{1}{4}$-mm. fraction are largely Miliolidae. These deposits are similar to those being formed in the present "barrier island flat" environment. Both shells and Foraminifera decrease somewhat in depth. These deeper deposits may represent "bay marginal" or inlet conditions, judged by the macro-organisms. A greenish, very stiff, silty clay was reached at about 30 feet. This presumably represents the Pleistocene Beaumont clay.

XMUD 11, a Porter sampler hole, was located at the west end of Mud Island on a sand flat exposed by the low tide which existed at the time. Here, again, it was anticipated that bay conditions would be reached at small depth because Mud Island has the appearance of having been built out onto Aransas Bay. The 4–8-foot sampling revealed material which consists of 75–90 per cent of a dominantly terrigenous sand. The sand has about one per cent of Foraminifera and somewhat smaller amounts of shells. Glauconite is scarce and the percentage of material in the $\frac{1}{8}$–$\frac{1}{16}$-mm. sieving is not as high as in "nearshore Gulf." It may represent either an inlet or a bay marginal deposit.

From 13 to 17 feet, where the next group of cores was taken, the constituents are radically different although the sand percentage is still about the same. Foraminifera and shells have almost disappeared, and the coarse fraction consists almost entirely of terrigenous minerals. Two roundness determinations of 0.39 and 0.40 are suggestive of dune origin. This deposit is similar to the cores found in the lower part of XSJ 61. It has 10–25 per cent of silt and clay so that it is unlike dunes of the present, despite the high degree of roundness of the sand. In fact, it does not entirely resemble any of the surface deposits of the area. In view of the scarcity of shells and Foraminifera, which is in contrast to all or nearly all present-day bay deposits, and the absence of glauconite and echinoids, which is in contrast to open Gulf deposits, it seems probable that this deposit was formed on land. In the next group of samples, extending from 22 to 26 feet, the same material continues although at the bottom of the hole the sand is green, suggesting that an older cycle may have been encountered.

The interiors of the barrier islands were sampled in three borings, all extending to depths of about 50 feet and two terminating in probable Pleistocene deposits. A boring, XMT 102, was located in the middle of Matagorda Island on the flats inside the coastal sand-dune belt. In the samples down to 30 feet the coarse fraction constitutes about 90 per cent of the total so that the material is largely sand. The first core at a depth of $4\frac{1}{2}$–5 feet was almost entirely terrigenous sand, with only 0.01 per cent of both shells and plant fibers. The roundness of 0.33 is intermediate between beach and dune values. The fact that almost the entire sample is found in the $\frac{1}{4}$–$\frac{1}{8}$-and the $\frac{1}{8}$–$\frac{1}{16}$-mm. fractions is suggestive of dune or beach origin. On the other hand, 2.6 per cent of silt and 5.4 per cent of clay are high for recent dunes or beaches in the area. Except for lower roundness coefficient, this is like the type of sample found underneath the surface at Jaybird Point and under the west end of Mud Island. The relatively high silt and clay contents may be the result of percolating waters carrying fines down into a beach or dune sand.

The two core samples in XMT 102 at $13\frac{1}{2}$–14 feet and $19\frac{1}{2}$–20 feet have 93 per cent sand and have similar coarse fractions. Shells constitute about 2 per cent and Foraminifera and echinoids a little more than one per cent. Glauconite is scarce whereas plant fragments and aggregates are found in both. The Foraminifera are indicative of either barrier island conditions or open Gulf but the general assemblage of constituents and the relatively low $\frac{1}{8}$–$\frac{1}{16}$-mm. fraction favor a barrier island environment. The samples at $26\frac{1}{2}$–27 feet and $28\frac{1}{2}$–29 feet have too much silt and clay for beach and shore and each have 70 per cent in the $\frac{1}{8}$–$\frac{1}{16}$-mm. sieve size which is more comparable with "nearshore Gulf" than with inlets or barrier flats. Glauconite and echinoids are sufficiently high in the $26\frac{1}{2}$–27-foot sample to suggest "nearshore Gulf" but are too low in the $28\frac{1}{2}$–29-foot core. The aggregates and plant fibers in both samples are more characteristic of an inlet or barrier flat than of open Gulf. The samples from 30 to 40 feet show a considerable increase in silt and clay. Glauconite is very low and the weight of the $\frac{1}{4}$–$\frac{1}{8}$-mm. sieving is like that of the $\frac{1}{8}$–$\frac{1}{16}$-mm. sieving. Plant fibers and aggregates are present. A barrier island environment is therefore suggested from several characteristics although the macro-organisms and Foraminifera could be either "nearshore Gulf" or barrier island. The $48\frac{1}{2}$–49-foot sample which contains echinoids and glauconite could be a shelf deposit although the 30 per cent clay and 32 per cent silt are too high for "nearshore Gulf" and there are plant fibers and aggregates which are rare in shelf deposits. It seems more likely that this sample was deposited in a barrier island environment.

Boring XSJ 60 is located near the middle of St. Joseph Island just inside the dune ridge. This hole yielded samples that are similar to XMT 102 except that the sand is consistently high throughout the length of the boring, nowhere becoming less than 75 per cent. The top of the boring at 9½–10 feet shows material which is almost entirely terrigenous sand and the roundness index of 0.37 puts it clearly in the dune-sand type. The Foraminifera are scarce, particularly in the finer sands, and only a trace of glauconite and small amounts of shell and echinoids were found. At 13½–14 feet the coarse fraction is 97 per cent, mostly in the ¼–⅛-mm. size. The Foraminifera are distinctly higher as are the shells. Large Miliolidae are abundant among the Foraminifera. This clearly was deposited in a barrier-island environment. At greater depths the silt and clay contents increase slightly but the general composition of the coarse fraction is not very different. Small amounts of glauconite are found in some of the samples. In none, however, is the percentage of ⅛–1/16 mm. as high as was found in all recent "nearshore Gulf" samples. The sediments appear to fit much better with inlet or barrier flat environments. Plant fibers and aggregates were found in some of the samples but no pyrite was noted. At 43½–44 feet a roundness of 0.36 suggests dunes. The sample from 59 to 59½ feet is oxidized and about 15 per cent of the coarse fraction consists of calcareous aggregates. The Foraminifera are scarce and appear to be worn. It is probably a land deposit of Pleistocene age.

Hole XSJ 59 is located in the center of a narrow part of St. Joseph Island, near Mud Island, and was drilled in a swale between two dunes. The sand content is high along the entire length of the borings. In the first sample from 8¼ to 9¾ feet the macro-organisms are characteristic of Gulf beaches, although some of them are found also in inlets. The sand content of 97.9 per cent is suggestive of a beach or dune, but the percentages of shells, echinoids, and Foraminifera are higher than in all dune and most recent Gulf beach samples in this area. Also the roundness index is only 0.30, much lower than that of dune sands. There is a larger percentage in the ¼–⅛-mm. sieving than in the ⅛–1/16-mm. which probably rules out the "nearshore Gulf" environment, leaving "Gulf beach" as the probable interpretation. At greater depths the sand content remains high but organisms are relatively rare as in recent beach and dune environments. None of the samples has sufficient material in the ⅛–1/16-mm. size to suggest "nearshore Gulf." At 28½–29 feet the roundness index is 0.34 which suggests it may have been a dune. At 39–39½ feet the roundness index is 0.33 which is on the line between beach and dune roundness. A "Gulf beach" environment appears to be the best interpretation of most of the samples in this considerable thickness of sand. At 52 feet a greenish sand, which is partly sandstone, and thus presumably cemented during Pleistocene time, has a low content of fine material, only 7½ per cent combined silt and clay. Besides the incipient cementation it differs from the overlying sands in having 2½ per cent of aggregates, mostly ferruginous.

A group of five holes were located along the wide straight beach which borders the Gulf side of both St. Joseph and Matagorda islands (Fig. 58). The northernmost of these holes, XMT 101, was located opposite the middle of San Antonio Bay. Because of time limitations only four cores were obtained at this locality. The sample at 4–4½ feet is 99.1 per cent sand with a roundness index of 0.32. The Foraminifera are scarce, but appreciable amounts of glauconite were found, and it is notable that some of the Foraminifera have a glauconite filling. The concentration of material in the ¼–⅛-mm. size is evidence against a "nearshore Gulf" environment so that a beach origin is likely. At 13½–14 feet the sand continues high and Foraminifera are still scarce. There is little sand in the ⅛–1/16-mm. size as compared with the ¼–⅛-mm., which again suggests beach origin rather than "nearshore Gulf." On the other hand, at 23½–24 feet the sample may be "nearshore Gulf." The Foraminifera have somewhat increased and the size distribution shows 66 per cent in the ⅛–1/16-mm. sieving which is almost as high as the typical "nearshore Gulf." The faunas could be either beach or "nearshore Gulf." A short distance lower in the boring there is a blue-green stiff clay which appears to be Beaumont. The coarse-fraction study of this indicates that it is a somewhat reworked Pleistocene bay deposit.

Boring XMT 100 is located 5 miles southwest of 101 and in line with XMT 102 and 103, as well as with the other borings along the San Antonio Bay traverse. In this hole, presumably Beaumont clay was encountered at depths between 35 and 43 feet. At 13½–14 feet the roundness of 0.36 is indicative of dune origin although there are rather surprisingly large percentages of Foraminifera, shells, and echinoids amounting, respectively, to 2.5, 1.6, and 2.0 per cent of the sample, and glauconite is well represented. These percentages are somewhat high for dunes, but the roundness is perhaps the best criterion. At 23½–24 feet the silt and clay content has increased to about 10 per cent whereas Foraminifera and glauconite have distinctly decreased. The 73 per cent in the ⅛–1/16-mm. sieving and the 10 per cent in the silt range may suggest "nearshore Gulf," despite the low glauconite. At 34½–35 feet there is an increase to more than 20 per cent of silt and clay. The 61 per cent found in the ⅛–1/16-mm. sieving is rather low for "nearshore Gulf" but the organisms are more suggestive of this environment than they are of barrier island types. The sample at 44½–45 feet is different from those above. Silt and clay have increased to 34 per cent but the chief difference is the presence of rather abundant coarse aggregates mostly of calcareous material. The material is weathered green or rusty brown and the clay is very stiff. There are streaks of white calcareous material which seem to represent fillings of surface holes. This sample was evidently taken near the contact of the Beaumont clay. At 56–56½ feet a very stiff rust-brown clay is clearly indicative of the Beaumont, although aggregates are less common at this depth than they were in the sample directly above.

Boring XSJ 58 was located along the beach just south of the entrance to Cedar Bayou inlet on St. Joseph Island. The core at 9–9½ feet has 96.7 per cent sand. Shells constitute about 14 per cent of the coarse fraction, echinoids almost 6 per cent, and glauconite 0.8 per cent. Six per cent of the material is coarser than

1 mm., consisting of shells and conglomerate. The material indicates either a "Gulf beach" or an inlet environment. Only 14.9 per cent of the sample is in the $\frac{1}{8}$–$\frac{1}{16}$-mm. size, which is too low to be "nearshore Gulf." At 23½–24 feet there is only 5.4 per cent silt and clay, and 8.1 per cent of the coarse fraction is coarser than 1 mm., including shells, pebbles, and aggregates. The macro-organisms and Foraminifera contain a mixture of open-Gulf and bay forms. The $\frac{1}{8}$–$\frac{1}{16}$ sieving contains 53 per cent, again too low for "nearshore Gulf," so that an inlet environment is suggested. At 38–38½ feet a stiff clayey material was encountered and the coarse fraction amounted to only 10 per cent. Both echinoids and glauconite are scarce. The sample is similar to sediment obtained in some of the circular lakes on Matagorda Island near Espiritu Santo Bay. The presence of plant fibers adds to the likelihood of its being related to barrier islands, and the fact that both glauconite and pyrite are found in the samples suggests the mingling of Gulf and bay environments. At 53–55 feet the core becomes sandy again, but it is high in evaporite. Foraminifera are almost missing, as are also echinoids and glauconite. It seems likely that this is a Pleistocene barrier island deposit which has been considerably weathered. The sand was found to continue down to 63½ feet although lenses of stiff brown clay and dark-colored pebbles came up in the cuttings.

Hole XSJ 57, 4 miles along the beach southwest of XSJ 58, yielded cores that are mostly sand although silt increases somewhat in depth. The first sample at 9–9½ feet has 97.7 per cent sand. The size distribution and 0.30 roundness index indicate a beach sand. At the depth of 23–23½ feet the sand content is reduced to 93 per cent, of which 68 per cent is in the $\frac{1}{8}$–$\frac{1}{16}$-mm. size. Echinoids and shells are abundant, most of them larger than 1 mm., and glauconite is plentiful. "Nearshore Gulf" seems to be the most likely environment of deposition, although the macro-organisms are somewhat suggestive of an inlet environment. Possibly a location in the deep entrance to an inlet might account for the high percentage of $\frac{1}{8}$–$\frac{1}{16}$-mm. sieving. Cuttings at 32 feet contain macro-organisms which are closely similar to those of Lydia Ann Channel, inside Aransas Pass, suggesting an inlet environment. At 38½–39 feet the sand has increased to 97 per cent and the shell and echinoid fragments larger than 1 mm. found at higher levels are no longer present. The $\frac{1}{4}$–$\frac{1}{8}$-mm. sieving is about equal in weight to the $\frac{1}{8}$–$\frac{1}{16}$-mm., which probably rules out "nearshore Gulf." The rounding value of 0.31 and the Foraminifera favor beach origin. At 52–52½ feet a few clay pockets are found in the sand. The echinoids are less abundant and glauconite has disappeared. The macro-organisms are distinctly those of lower-bay or inlet environments, similar to those coming from the higher cuttings. Thus, the barrier-island environment may have been crossed in the interval from 23–52 feet. At 60–61 feet the sample is rust-brown sand containing 2 per cent of aggregates, and is probably from an older Pleistocene cycle. At 68 feet, cuttings show typical Beaumont clay with some sand pockets.

Boring XSJ 56 was located on the Gulf shore opposite Mud Island. This was drilled to a depth of 65 feet where the Beaumont clay was encountered. Above the clay, all samples are sands, nowhere with more than 4.6 per cent silt and clay. At a depth of 8½–9 feet the material has 98 per cent sand and fits entirely into beach characteristics. It has too much coarse material to suggest dune origin, and the roundness of 0.30 is indicative of beach sands. It has a larger ¼–⅛-mm. than ⅛–1/16-mm. fraction, which rules out "nearshore Gulf." At a depth of 18–18½ feet there is a little more silt and clay (3.4 per cent) and the 65 per cent in the ⅛–1/16-mm. size is more in line with "nearshore Gulf." Echinoids and glauconite are also well represented. On the other hand, typical beach Foraminifera are surprisingly abundant, much more common than in any of the "nearshore Gulf" samples in the recent sediments. In the next sample at 28½–29 feet the sand has 97 per cent, of which ¼–⅛-mm. size exceeds the ⅛–1/16-mm. Also glauconite is very scarce, suggesting that it is not an open Gulf sample. There is too much coarse material for it to be a typical dune sample although the roundness of 0.34 is marginal between dunes and beach. Beach seems to be the best interpretation. Cuttings during the drilling suggested there may be a shell concentrate at 30–32 feet and again at 35–38 feet. The shells from the 30–32-foot cuttings look like beach types but the 35–38-foot shells are much more suggestive of bays or inlets and show clearly that there was some connection with the bays during the deposition of the material. At 38–38½ feet the sample is again suggestive of beach conditions, having 97 per cent sand and only 30 per cent in the ⅛–1/16-mm. size and a scarcity of glauconite. Roundness of 0.33 is somewhat more akin to beach than dune sand. At 46–46½ feet fairly large shells become an important item. A Carbon-14 age on these shells was 6,500 ± 500. These include many bay shells along with some that are characteristic of Gulf beaches. The silt and clay have increased to 4½ per cent. It seems likely that this is an inlet deposit which had relatively strong currents. The shell concentrates in Lydia Ann Channel are similar in character. At 56–56½ feet the sand showed a brownish stain, and the Foraminifera are much worn. The 90 per cent sand in the ⅛–1/16-mm. size may suggest "nearshore Gulf," but the shells are more suggestive of bay origin and the absence of echinoids and glauconite may rule out the "nearshore Gulf" environment. The presence of a few aggregates and the brown stain suggest that the sediment may be reworked or weathered material. At a slightly greater depth typical Beaumont clay came up in the cuttings.

OPEN GULF BORING

A boring obtained from the Humble Oil and Refining Company platform in 42 feet of water off St. Joseph Island near Cedar Bayou has revealed the presence of probable Pleistocene at a depth of 80 feet below the sea bottom. At a depth of ½–1 foot, sand amounts to only 18.2 per cent, mostly terrigenous. The Foraminifera and macro-organisms are indicative of shallow-Gulf conditions. The echinoids and glauconite have an abundance characteristic of the present depth. The sample at 9½–10 feet shows an increase to 43 per cent sand. The Foraminifera and macro-organisms are a little more characteristic of shallow water than are those found at ½–1 foot. At 13½–14 feet a very curious sample was found which has only 4.8 per cent sand. This is a lower percentage than any obtained on the inner continental shelf in this vicinity. Furthermore, the material lacks the glauconite of shelf samples and is far too high in plant fibers although some of the latter are sargassum and hence indicative of marine conditions. The fauna contains a curious mixture which is not diagnostic. At 14–14½ feet the coarse fraction has increased to 66½ per cent. Echinoids have also increased and a small amount of glauconite is found. The ¼–⅛-and ⅛–1/16-mm. sievings have about 27 per cent of the whole. Also the shells are very abundant and include forms which are a combination of bay and open Gulf, whereas the Foraminifera are more related to the beach fauna. An inlet environment seems to account best for the other characteristics. At 23½–24 feet glauconite has disappeared, the coarse fraction has increased to 97.4 per cent, and Foraminifera have become very scarce. The roundness coefficient is very high, 0.42, making it seem very probable that this is a dune sample. In the next available sample at 59–59½ feet the sand amounts to 89 per cent, mostly terrigenous. There are very few Foraminifera, few echinoids, and no glauconite. The macro-organisms are indicative of beach environment. The roundness is 0.33 which is low for a dune. It seems likely that this material represents a barrier flat, possibly an overwash deposit. At 70½–71 feet the coarse fraction has dropped to 47.4 per cent. Foraminifera include the large size of Miliolidae commonly found on barrier islands. The deposit may represent a channel in a barrier island which, as indicated by the absence of glauconite, may not have been connected to the open Gulf. At 71½–72 feet the coarse fraction is still lower, amounting to only 23 per cent. There are no echinoids or glauconite. The shells have considerably increased and are indicative of a bay with rather low salinity. Below 78 feet the formation changes with a large increase in clay and, according to measurements made by the Humble Oil and Refining Company, has a high shear strength. This deposit was interpreted by the Humble geologists as probably representing Pleistocene.

The general log of the boring given by the Humble Oil and Refining Company indicates that the first 19 feet are a combination of sand with some shell zones and a little clay, and below that to the probable Pleistocene at 78 feet there are interbedded sands and clays. In view of this log and the description of the samples, the writers have concluded: (1) that open Gulf formations extend only to about 10 feet below the sea floor, (2) that barrier island conditions follow to a depth of about 71 feet, and (3) bay conditions are encountered before reaching the Pleistocene at 78 feet. The lower part may be somewhat reworked. This sequence suggests that barrier islands existed farther seaward during the rise in sea-level at the end of the Pleistocene, than they exist at present.

RATES OF DEPOSITION, CARBON-14, AND FORAMINIFERA ABUNDANCE

In some parts of the Texas bays a comparison between the detailed Coast and Geodetic Survey soundings made in the last century with equally detailed soundings in the 1930s has shown definite indications of shoaling (Shepard, 1953).

Elsewhere the evidence is less certain but the great majority of soundings suggests shoaling which averages a little more than one foot per century. According to these soundings the bays of the Rockport area seem to have had about the average amount of fill. If this rate had continued during the 9,800 years indicated in Carbon-14 determinations for the oldest sediments in the San Antonio Bay borings, more than 100 feet of deposition should have taken place. Actually the 9,300 years for 69 feet found in boring XS 383 gives a rate of 0.74 foot per century. In view of the compaction in the sediments this is not very much out of line with indications of shoaling. The rate does not, on the other hand, allow for any subsidence such as appears to be indicated from the Coast and Geodetic Survey tide-gauge station at Galveston (Marmer, 1952).

The finding of a 2,100-year age for the top 5 feet of deposition in the center of San Antonio Bay (XS 384) indicates a rate at this point of only 0.24 foot per century, much slower than the average, although this rate comes from a position on an oyster reef. These reefs are normally elevated above the bottom of the bay so that deposition was probably somewhat faster than indicated.

Another means of attacking the problem comes from a study of the abundance of Foraminifera. Unless the Foraminifera are locally concentrated, their abundance should show an inverse relationship to the rate of deposition of terrigenous material. This would, of course, be dependent on a relatively uniform rate of production of Foraminifera. This assumption was made for the fine sediments underlying San Antonio Bay, excepting where oyster reefs complicate the picture.

The use of Foraminifera as an index became meaningful when it was noted by Moore (1955) that the percentages show consistent increase at a depth of a few feet below the top of the bay borings and a consistent decrease at greater depths. Considerable similarity was found in the general nature of the curves and in order to verify this, two continuous borings were made with the Porter sampler to depths of about 25 feet each. One already discussed was at the end of the Guadalupe Delta and the other, made very recently, was in lower-middle San Antonio Bay. When the detailed Foraminifera percentages of these borings are plotted against depth (Fig. 65A) it is seen that there is a rather remarkable consistency in the resulting curves. The double maxima shown in Figure 65B may be significant inasmuch as maxima at two rather distinct levels were found in the other borings which had more widely spaced cores.

By use of the average Foraminifera percentage throughout the column and the average age indicated by the Carbon-14 dating at 55 feet, the rates at each 2½-foot interval were computed, and a curve showing the rates of deposition during the past 8,000 years was developed[19] (Fig. 65, C and D). As the result of the Foraminifera study combined with Carbon-14 dating, it becomes evident that deposition was somewhat slower in a period of about −500 to −5,000 years than it has been recently and that deposition was much faster than now between about −5,000 and −7,000 years. Prior to −7,000 the calculations show deposition to have been relatively slow, but not as slow as in the −500 to −5,000 year period.

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[19] This average did not include the estimates from the delta borings because of different environmental influences which affect the delta and near-delta deposits of the upper 10–15 feet of the sediment column.

Comparison between the Foraminifera in the bay sediments found in the borings under Guadalupe Delta with those of San Antonio Bay (Fig. 65A) shows that the Foraminifera maxima are considerably deeper in XG 17 which is 5 miles up-delta than under the bay. Down-delta and approaching the bay, the maxima

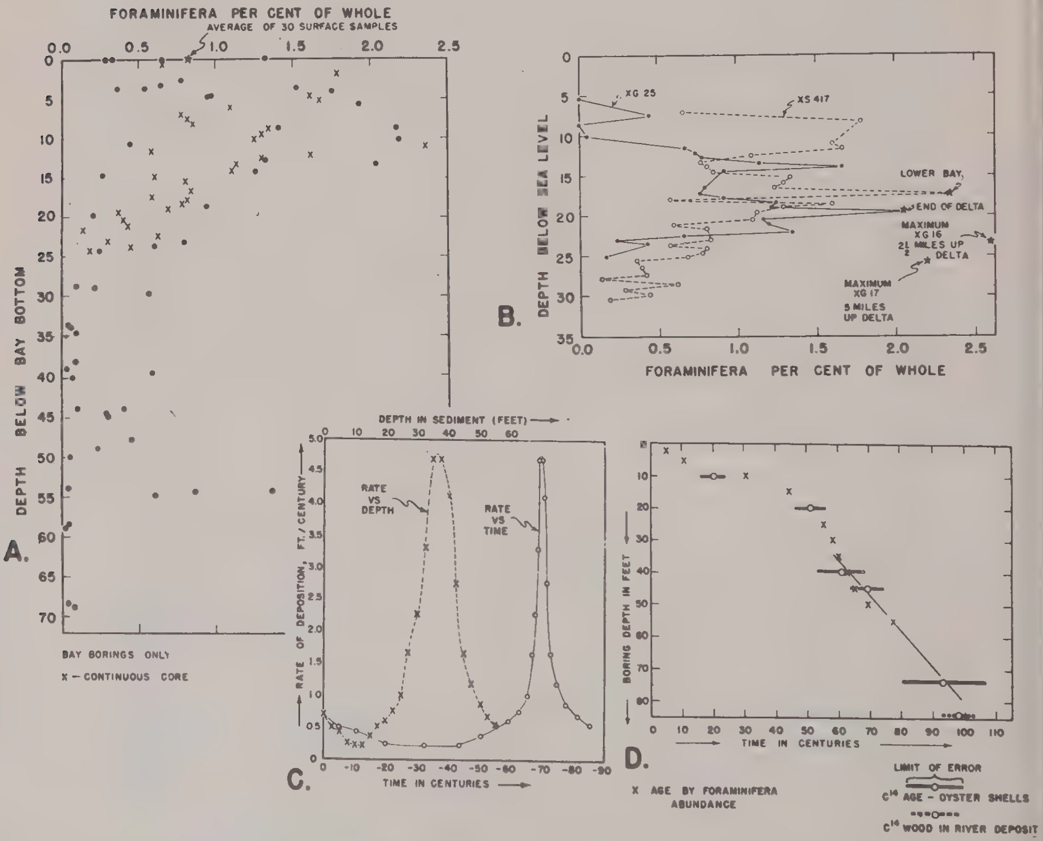

FIG. 65.—Relation of Foraminifera to depth in borings. A. In San Antonio Bay borings. B. In two continuously cored borings XG 25 at delta end and XS 417 in lower middle San Antonio Bay, both related to sea-level. Resemblance of two curves. Foraminifera maxima in XG 16 and XG 17 become deeper updelta. C. Rate of deposition based on Foraminifera abundance plotted against time. Inverse curves for rate *vs.* depth and rate *vs.* time. D. Age at various depths below bay floor based on Foraminifera abundance and Carbon-14 dating.

become closer to the bay conditions so that XG 25 at the delta tip has the maxima horizons at levels which are only slightly lower in reference to sea-level than found under the bay. The reason for greater thicknesses of sediment in the delta is easily understood because of faster deposition rates at stream mouths, which have occurred in many other places along the Texas coast (Shepard, 1953).

The varying rates of deposition may provide pertinent data relative to the hypothesis that the sea stood about 6 meters higher than it stands now during a climatic optimum 4,000–7,000 years ago and that it dropped to the present level somewhat later (Umbgrove, 1951, Flint, 1953, and Antevs, 1954). Bearing on this hypothesis is the probability that the bay was more extensive than now during much of the period of slow deposition between about −500 and −5,000 years.

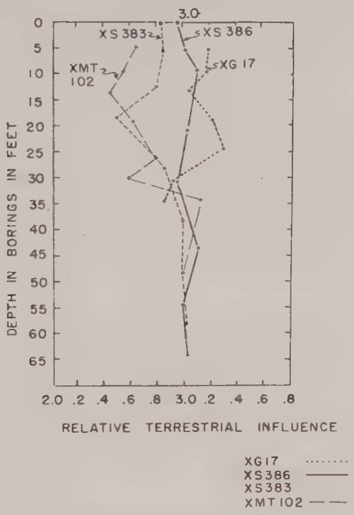

FIG. 66.—Variation in terrestrial influence shown by relation of fresh-water to salt-water bacteria along lengths of four borings. Data from D. E. Contois.

BACTERIOLOGICAL RESULTS FROM BORING OPERATIONS

Results of analyses of samples collected during the drilling and boring operations in the Rockport area during October, 1953, are of particular interest in regard to terrestrial influences as indicated by bacteria in the deposits. Figure 66 shows the relative terrestrial influence measured by ratios of terrestrial bacteria to marine bacteria at various depths in different localities. Hole XG 17, located in the Guadalupe Delta (Fig. 44 shows locations), shows a general decrease in terrestrial influence with depth, indicating the outward growth of the delta.

Samples from the bottom of this hole (at 30 and 35 feet) are indicative of present conditions in upper San Antonio Bay, that is, lower terrestrial influence and higher pH. Hole XS 386 in upper San Antonio Bay shows no appreciable change in terrestrial influence throughout. The borings from lower-middle San Antonio Bay, XS 383, show first a decrease then an increase in terrestrial influence with depth, like hole XMT 102 in the barrier flat of Matagorda Island. The net increase is greater in XMT 102.

Since terrestrial influence is apparently the same toward the bottoms of all the holes irrespective of locality, river influence in the bay may have been greater and more uniform in times past. This influence has apparently had a general decrease to the present, excepting in the northern end of the bay where the encroaching delta has maintained it at a high level.

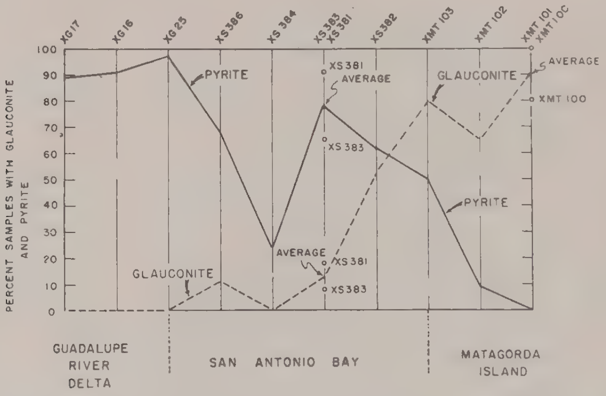

FIG. 67.—Percentage of samples with pyrite and glauconite in series of borings from Guadalupe Delta to Gulf Coast of Matagorda Island. Irregularity in pyrite profile in XS 384 is related to continuous oyster-reef environment found in that boring. In two cases, percentages have been averaged from data from two adjacent holes.

GLAUCONITE AND PYRITE IN BORINGS

Most of the samples obtained during the boring operations had sufficient pyrite or glauconite so that it was recorded in studying the sievings under the binocular microscope. The percentage of samples from each hole having pyrite and the percentage having glauconite when plotted in relation to the traverse from upper Guadalupe Delta to outer Matagorda Island indicate a progressive change from pyrite to glauconite (Fig. 67). In the series of holes made in the delta almost all of the samples have pyrite, the few exceptions being in the surface delta deposits. No glauconite was found under the delta and only a rare grain in the upper bay. Pyrite is found in the upper and middle-bay borings except in the samples from the oyster-reef zones. Since the latter constitute the bulk of the only middle-bay boring (XS 384), the abundance of pyrite in other types of bay deposits within this zone is unknown. In the borings of the lower bay, pyrite is abundant but glauconite is also represented in a considerable number of samples. In the boring near the barrier island, pyrite has fallen off and glauconite increased. Glauconite continues to increase across the island and pyrite decreases to zero in the beach borings.

In relation to depth in the holes, no change was found under the delta and in the upper and middle bay, but in the lower bay, where there is a northeast-southwest line of five holes (Fig. 62), four show an increase of pyrite with depth and a decrease of glauconite. The same is shown very definitely in the hole near the barrier island where glauconite is more abundant in the upper four samples, whereas five out of the underlying seven samples have more pyrite. On the north side of Matagorda Island, the glauconite is found exclusively in the upper samples but is dominated by pyrite in the three bottom samples. In the middle of the island pyrite is absent in the upper five samples but is present in four out of the next five, and in one dominates the glauconite. The borings in the beach show little change relative to the two minerals except XSJ 58, which has an increase of pyrite in depth.

The changes in abundance of pyrite and glauconite in relation to distance from

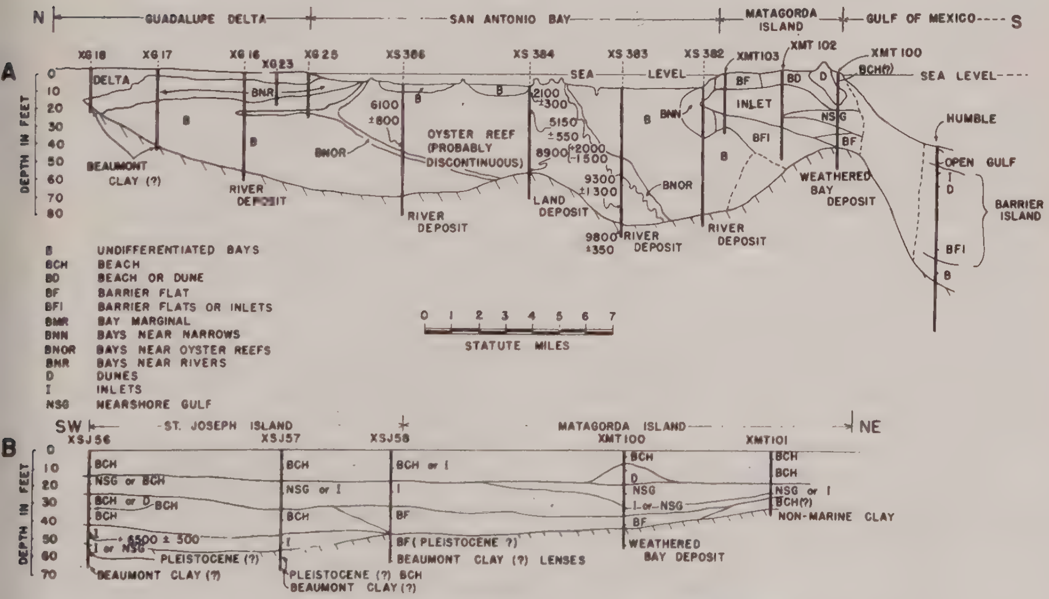
N
GUADALUPE DELTA
SAN ANTONIO BAY
MATAGORDA ISLAND
GULF OF MEXICO
S
A
XG18
XG17
XG16
XG23
XG25
XS386
XS384
XS383
XS382
XMT103
XMT102
XMT100
DEPTH IN FEET
0
10
20
30
40
50
60
70
80
DELTA
BNR
B
SEA LEVEL
BF
BD
D
BCH(?)
INLET
NSG
BFI
BF
BNN
HUMBLE
OPEN GULF
I
D
BARRIER ISLAND
BFI
B
6100 ±800
2100 ±300
5150 ±550
8900 +2000 -1500
9300 ±1300
9800 ±350
OYSTER REEF (PROBABLY DISCONTINUOUS)
BNOR
BEAUMONT CLAY (?)
RIVER DEPOSIT
LAND DEPOSIT
WEATHERED BAY DEPOSIT
B UNDIFFERENTIATED BAYS
BCH BEACH
BD BEACH OR DUNE
BF BARRIER FLAT
BFI BARRIER FLATS OR INLETS
BMR BAY MARGINAL
BNN BAYS NEAR NARROWS
BNOR BAYS NEAR OYSTER REEFS
BNR BAYS NEAR RIVERS
D DUNES
I INLETS
NSG NEARSHORE GULF
0 1 2 3 4 5 6 7
STATUTE MILES
SW
ST. JOSEPH ISLAND
MATAGORDA ISLAND
NE
B
XSJ56
XSJ57
XSJ58
XMT100
XMT101
BCH
NSG or BCH
BCH or D
BCH
6500 ± 300
I or NSG
PLEISTOCENE (?)
BEAUMONT CLAY (?)
NSG or I
I
PLEISTOCENE (?) BCH
BEAUMONT CLAY (?)
BCH or I
BF
BF (PLEISTOCENE ?)
BEAUMONT CLAY (?) LENSES
D
NSG
I or NSG
WEATHERED BAY DEPOSIT
BCH(?)
NON-MARINE CLAY

FIG. 68.—Interpretations of depositional conditions along north-south line (A) and northeast-southwest line (B). Interpretation of each sample is given on B, whereas it is omitted on A because most samples are too closely spaced in north-south line to make inclusion possible. Interpretations are subject to some uncertainty and the boundaries are only approximate. For locations see Fig. 58.

the Delta and from the open Gulf show that for a considerable period preceding the present the Gulf influence represented by glauconite (Fig. 28) was similar to what it is now. An exception is found in the lower bay and under the barrier island where glauconite decreased with depth so that these parts of the bays must have been more isolated from the Gulf than they are now. Since a small amount of pyrite is found in the surface barrier island and open Gulf samples, the absence of pyrite in the samples under the barrier island may indicate that it has not been preserved. The concentration of pyrite in some of the samples under the Delta and under the bay is certainly far higher than any found in the top sediments in any of the present environments of the area.

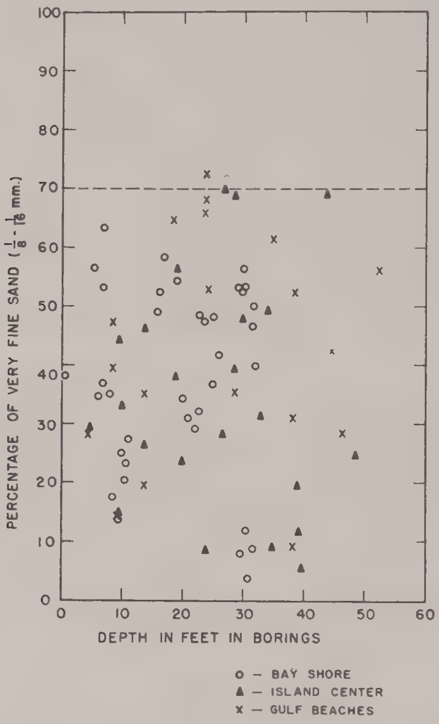

FIG. 69.—Percentage of very fine sand ($\frac{1}{8}$–$\frac{1}{16}$ mm.) found in the samples from borings under barrier islands. Compare Fig. 51.

SUMMARY OF TRI-DIMENSIONAL INVESTIGATIONS

Figure 68 summarizes the general conclusions which have come from the borings made (1) along a line extending from the Guadalupe Delta to the outer Matagorda Island beach, and (2) along a line which follows the barrier island beaches. From these diagrams it may be seen that the sediment section extending from about 30 to 80 feet below the present surface was deposited under conditions differing little from those now existing. The cores under the beaches yielded evidence that the barrier islands have existed as islands or shoals during the deposition of almost all of the thick sand sections and over a period of at least 6,500 years. Similarly the sheltered bay conditions must have persisted over a long period, probably since the sea came into the area about 10,000 years prior to the present.

The following evidence for this persistence of conditions is found.

1. All but one of the samples of sediment underlying the barrier islands lack sufficient sand in the $\frac{1}{8}$–$\frac{1}{16}$-mm. grade size to be comparable with "nearshore Gulf" deposits (Fig. 69).

2. Oyster-reef conditions occupy a very large proportion of the entire boring in the holes of the central part of San Antonio Bay (Fig. 68).

3. Ten samples from the San Antonio Bay borings at depths of 3–55 feet yielded as large percentages of Foraminifera in the $\frac{1}{2}$–$\frac{1}{4}$- and $\frac{1}{4}$–$\frac{1}{8}$-mm. sieve sizes as are found in surface samples of the deeper portions of Aransas Bay.

4. In general the pyrite characteristic of sediments under the bays persists to the bottom of the holes (Fig. 67). Similarly, the glauconite which is more characteristic of the barrier islands persists to the bottoms of the island holes.

5. The faunas change very little in depth in the holes, indicating only a slight relative increase or decrease of salinity in the borings underneath the bays.

6. Carbon-14 determinations indicate a minimum age for the duration of bay conditions of about 9,500 years and of barrier islands of 6,500 years.

Real changes of condition were found, however, in several places. The borings in the Guadalupe Delta show that only a few feet of true delta deposits exist and these are underlain by bay deposits, the uppermost showing clear evidence of nearness to the river mouths, but the deeper beds indicating central-bay conditions. A less consistent change was found in the barrier flat environments, and on Matagorda Island indications are that the barrier flat deposits have overlapped onto bay deposits. The ratio of percentage of Foraminifera in $\frac{1}{2}$–$\frac{1}{4}$-mm. sievings to percentage in $\frac{1}{4}$–$\frac{1}{8}$-mm. decreases downward in the boring on the north side of Matagorda Island, giving further evidence that true bay conditions existed (Fig. 35). On the other hand, along the bay shores of St. Joseph Island and Mud Island the borings revealed examples of a curious deposit which has indications of deposition on land, possibly in the form of dunes although they contain a far higher percentage of fine sediment than is characteristic of the present dunes.[20] In the offshore drillings made by Humble and Gulf oil companies, the samples indicate a change from open Gulf conditions to barrier island and eventually perhaps to bay conditions before reaching the Pleistocene.

The general conclusion which can be obtained from the boring operations is that the barrier islands developed during the melting of the Pleistocene glaciers and grew up as the sea-level was rising to its present level. As a result of the upgrowth of the barriers, protected bay conditions began almost as soon as the sea came into the deep inner valleys of the area, and these bay conditions have persisted during and subsequent to the rise of sea-level. The barrier islands of the Rockport area probably migrated shoreward during this rise although elsewhere they may have grown gulfward. It is not unlikely that more than one chain of barrier islands existed in the region during this rise in sea-level.

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[20] This same material was found south of the Rockport area at a depth of 22 feet under the northern end of Padre Island $\frac{1}{4}$ mile from the beach.

The depth of the bays during the rise is not easily determined from available information although the finding of the high foraminiferal contents in many of the cores from under San Antonio Bay, which was also found in the surface sediments of relatively deep water of Aransas Bay, suggests that San Antonio Bay also may have been relatively deep during and subsequent to the sea-level rise. Unfortunately, the oyster reefs, which were so persistent during the rise, give little testimony about the depth, since oyster reefs of the same type are known to grow in water as deep as 100 feet in Chesapeake Bay.

As a result of this upward growth of the barriers during sea-level rise the bay deposits have been found to have thicknesses up to at least 80 feet under lower San Antonio Bay, whereas 60 feet of barrier-island sand were found under a part of the beach on St. Joseph Island. Accordingly, thick stratigraphic units must have formed during this Pleistocene episode and it is not unlikely that similarly thick sand lenses of this sort may have formed during earlier glacial periods such as during the Permo-Carboniferous (Wanless and Shepard, 1935). Other deposits of this kind could have formed due to sea-level changes from other causes or due to sinking of the land at rates comparable with the rise in sea-level produced by the melting Pleistocene glaciers.

EARLY DIAGENESIS

Diagenesis is the summation of processes which act to alter the physical or chemical composition of a sediment from its initial formation to lithification. The initial phases of diagenesis are less well known than are the later stages preceding this conversion from unconsolidated sediment to rock. This condition is the result of difficulties in sampling and the complexity of the chemical and physical environment of recently deposited sediments. In fact the exact time at which the alteration of a sedimentary particle should be considered as diagenesis is subject to uncertainty inasmuch as a given particle may be deposited, resuspended, and redeposited many times before it is actually incorporated into the geologic column. In the following discussion diagenesis is not considered to begin until the sediment in question has reached its final resting place in the current cycle of erosion, transportation, and deposition. Changes or alterations of the particles which take place before this final deposition are not considered as diagenesis but as adjustments of the particles to their environment.

One method of studying early diagenesis is to measure changes in the physical and chemical structure of the sediments which occur with increasing depth of burial. The factor which must be held constant in such a study is environment. Emery and Rittenberg (1952) have used this approach with success in their study of the basin sediments off the California coast where the environment must have been essentially constant over long time periods.

The environment of deposition in the shallow nearshore waters of the central Texas coast, however, may fluctuate laterally as shown earlier in this report. These lateral fluctuations result in vertical changes in the sedimentary column. Before any interpretations of diagenetic changes are attempted, therefore, the sample must be carefully studied for indications of a change in environment of deposition.

Two groups of cores were collected in the Rockport area for the purpose of studying early diagenesis (Fig. 44A). Four cores about 8 feet in length were recovered from the Guadalupe River, San Antonio Bay, Aransas Bay, and the Gulf of Mexico. These were analysed physically, chemically, and biologically. In order to learn the effects of burial to greater depth, two borings in San Antonio Bay, one in the Guadalupe River delta, and one in Matagorda Island were sampled at regular intervals for analysis of the sediment and its interstitial waters.

PHYSICAL CHANGES

The most obvious physical change with depth in a sediment of nearly constant texture is variation in color and plasticity. In most areas of fine sediments the upper 1–3 centimeters of a core consist of a brown fluid layer. Below this the sediment is normally a shade of gray and is somewhat firmer. There is some question whether this brown fluid layer should be considered as an integral part of the sediment column. In the shallow environment of this area even relatively gentle winds are able to generate waves capable of resuspending this uppermost brown material. It is therefore a "mobile" zone which includes a sharp gradient from very turbid water to very fluid sediment. Below this mobile layer are less obvious changes in the appearance of the sediments. Plasticity in general increases, probably as a result of a decreased water content in the sediments. No fixed rules can be made on this subject, however, because the relationship of change in water content with depth is not fully understood.

Water content and specific gravity.—Previous studies of changes in water content with depth of burial have shown varied results. Arrhenius (1952), in studying the deep sea cores from the Swedish expedition of 1947–1948, found no uniform change in water content with depth but instead a variation with clay content and some correlation with state of hydration of calcium carbonate present in the sediments. Emery and Rittenberg (1952) found that the sediments from the basins off the California coast showed a rather consistent decrease in water content with depth, particularly in the upper few centimeters of the core. They attributed this water loss to compaction and upward percolation of interstitial water with increased pressure. A contrast between the California basin sediments and those of the Texas coast is notable in respect to near surface-water content. The eleven California basin cores showed an average decrease in moisture content (percentage of dry sediment weight) of about 45 per cent between depths of about 2 and 10 inches. The average median diameter of the sediment was 5.3 microns and decreased an average of only about 0.5 micron over this same depth interval. However, cores high in clay from four environments of the Rockport, Texas, area decreased an average of only 5 per cent in moisture content between depths of 2–10 inches. The average median diameter was 2.24 microns and the decrease in size was 4.05 microns for the interval.

In both the California and Texas sediments the method of determination of water content was the same, that is, by weighing a part of the raw sediment, drying at 105°C., then reweighing. The loss in weight is taken as water and the water content can then be computed as percentage of dry sediment or as percentage of wet sediment. Figures 70 through 72 show the water content of the cores and borings from the Rockport area computed as percentage wet weight. The most striking feature about these figures is the correlation of water content to the percentage of clay. Changes in water content here are very clearly related to the sediment texture. Figure 73A shows these water-content values plotted against clay content. A strong correlation is evident. For comparison, a group of samples from a region of very rapid deposition off the Mississippi River Delta were plotted on the same diagram. Water contents from the sediments of both areas are apparently straight-line functions of the amount of clay present but the axes are notably different. Water content of the Rockport area sediments is evidently more sensitive to changes in clay content, or in other words, a relatively larger proportion of the total water content of the sediment is contained in the clay fraction. This suggests that variations in rate of deposition may be a real influence on the water content *versus* depth relationship. This may explain in part the differences between the Rockport area sediments and those of the California basin inasmuch as the latter are deposited at a slower rate. Figure 73B shows the same water-content data plotted against median diameter rather than clay content. Again good relationship exists between size and water content, but the separation between Rockport and Mississippi Delta sediments, which is obvious in Figure 73A, is lost in plotting median diameters. This is a good example of the poor sensitivity of median diameter as a parameter of size description. In many cases relationships are lost when only median diameters are used as a size indicator. This has been especially true in the finer sediments.

The influence of environment in changing water content is clearly shown in Figure 72B in which is plotted the data from San Antonio Bay boring XS 386. As this boring passed through the environment of an oyster reef, the texture was strongly affected by the coarse oyster shells. The water content in turn decreases within the limits of this deposit.

Specific gravity of the sediments from cores G 15D, S 334D, A 190, and J 72

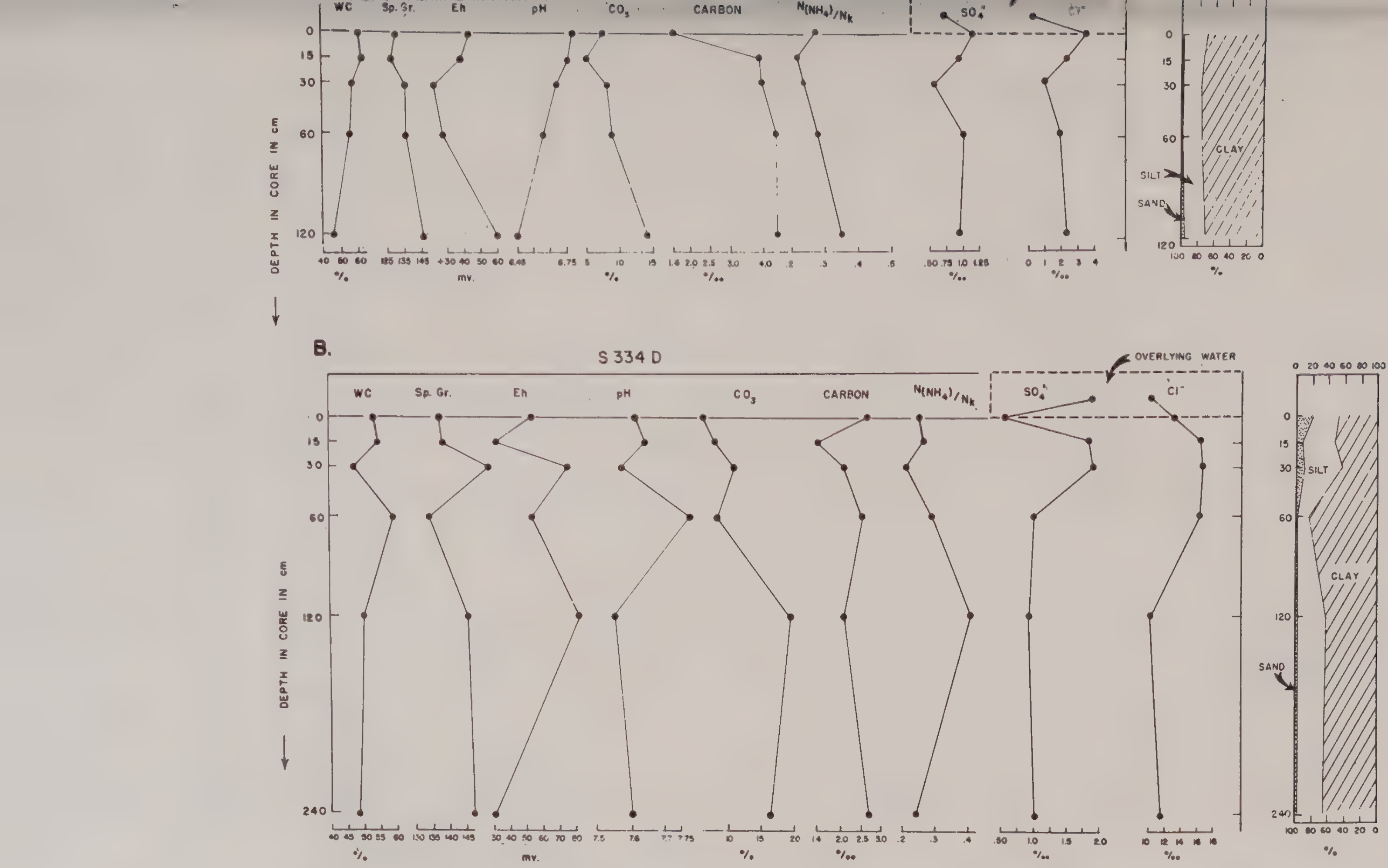


Fig. 7p.—Showing variations in physical and chemical properties of sediments with depth of burial. Two environments represented: Aransas Bay (A 190D) and open Gulf of Mexico (J 72D).

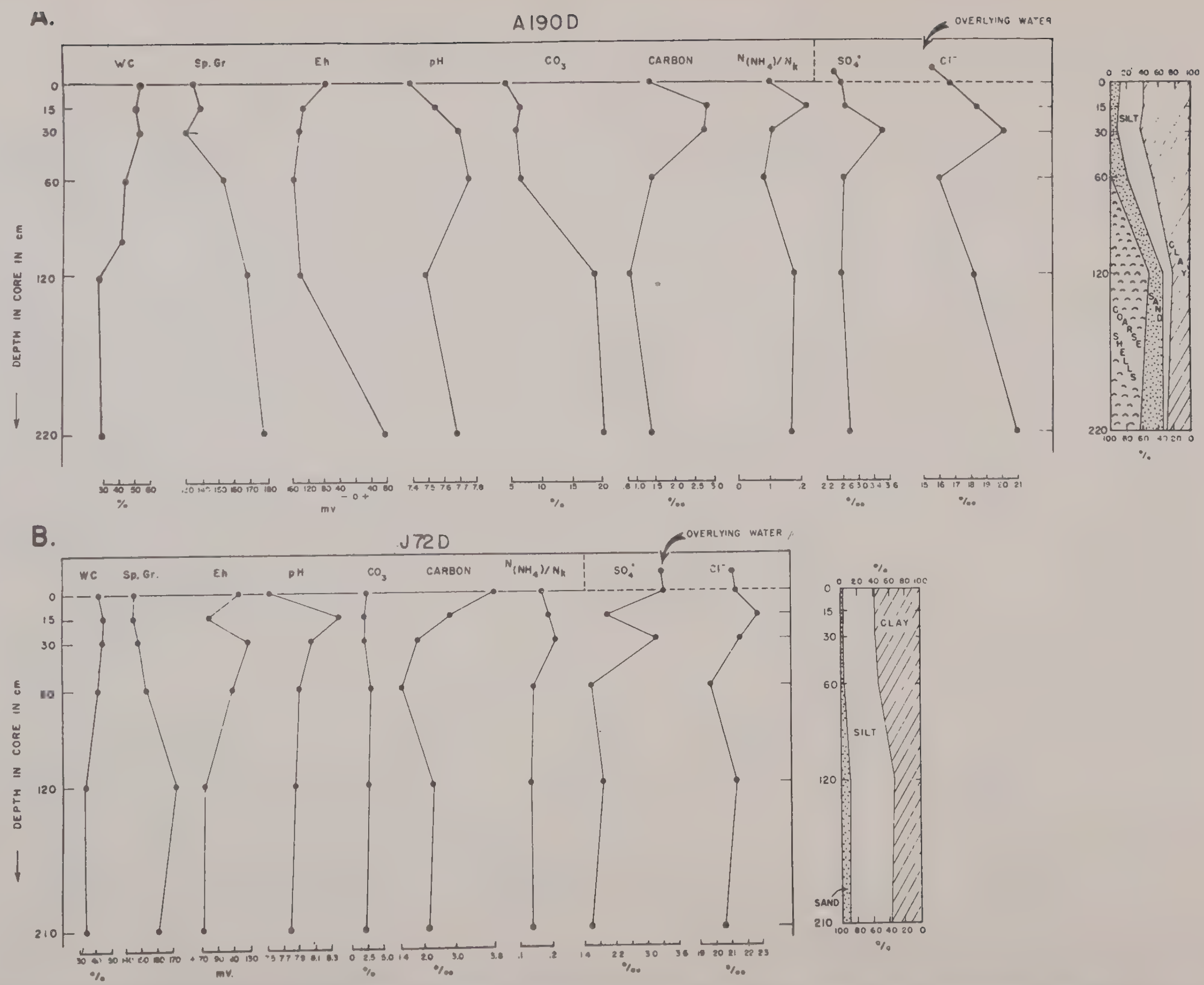


FIG. 71.—Variations in physical and chemical properties of sediments with depth of burial. Two environments represented: Guadalupe River (G [illegible]D) and San Antonio Bay (S [illegible]D)

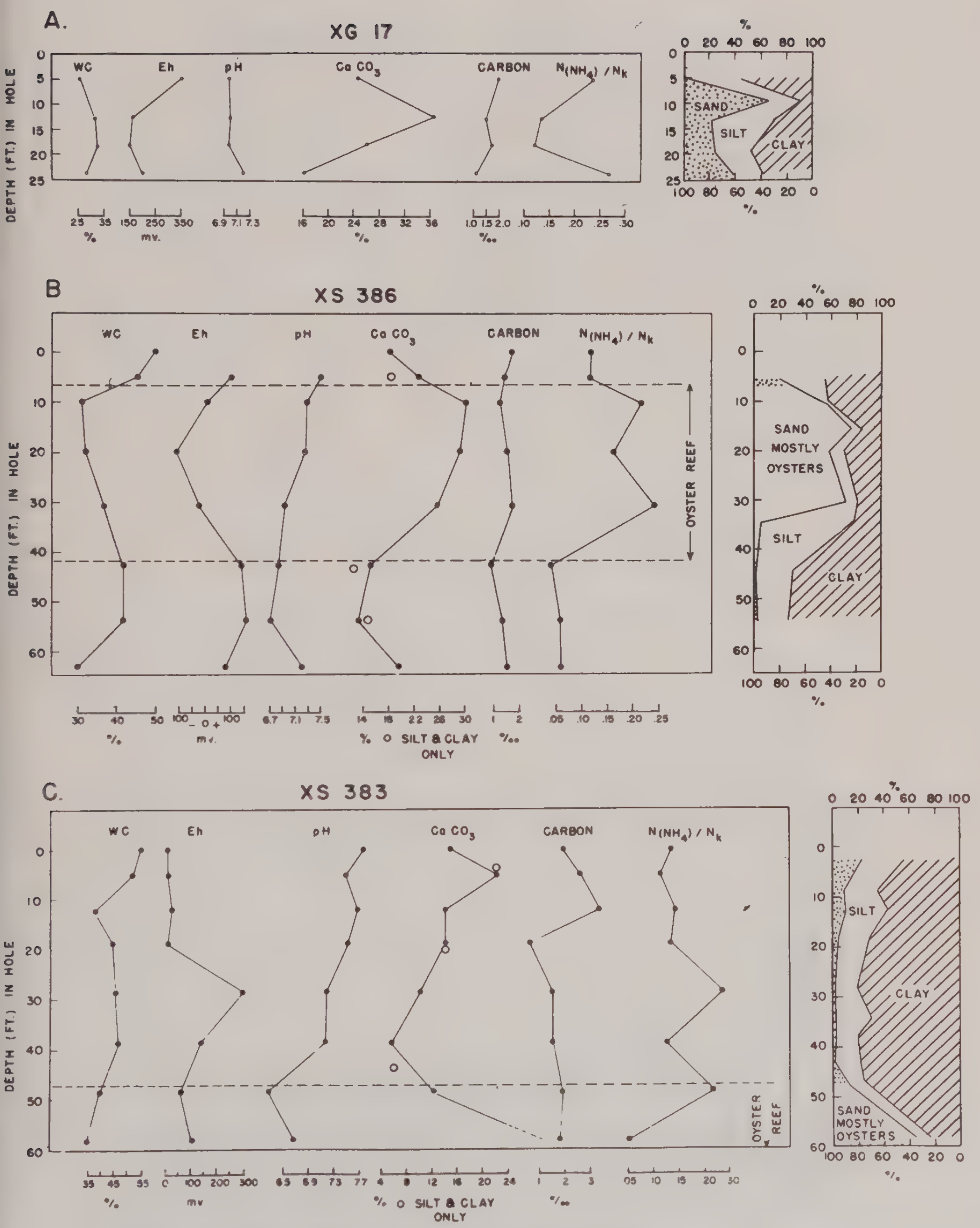
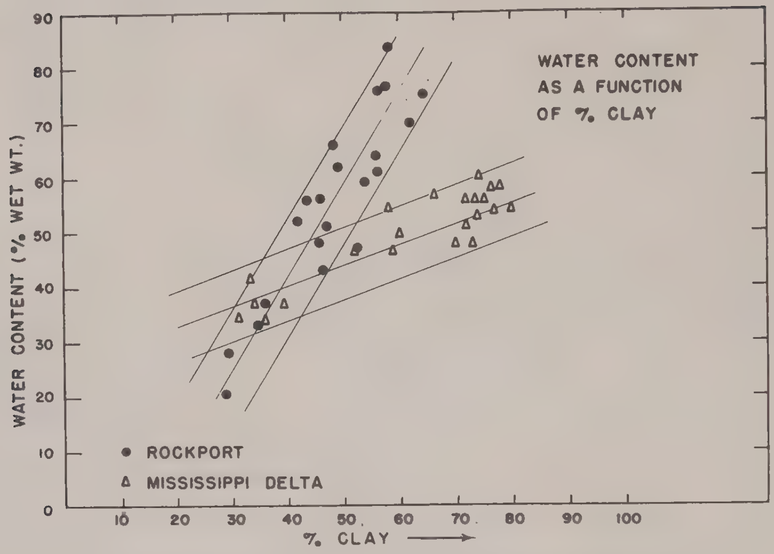


Fig. 72.—Physical and chemical variations in sediments with depth of burial. "A" is a boring through Guadalupe Delta, and "B" and "C" are in San Antonio Bay. These extend down to maximum depths of 60 feet.

A.



B.

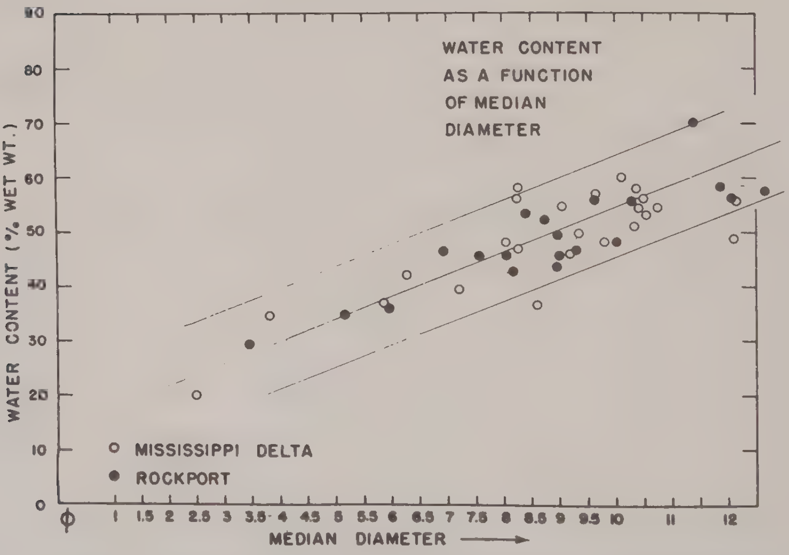


FIG. 73A.—Correlation between water content and percentage of clay. Correlations in Rockport and Mississippi Delta samples are equally good but lie along different axes.

FIG. 73B.—Correlation between median diameter of sediments and water content. No good separation of Rockport and Mississippi Delta areas indicated in this plot.

is shown in Figures 70 and 71. These were determined by first weighing a container of known volume (about 5.5 cc.), filling with sediment, and reweighing. This method is reasonably accurate if care is exercised in filling the container to be certain that all air pockets are excluded and that no large shells or other foreign materials are included. The plots of specific gravity show a good correlation with water content and hence percentage of clay in the sediment. It can be seen particularly in Figure 70B, however, that there is a tendency for the specific gravity of the sediment to become somewhat greater than the change in percentage which clay and water content would warrant. This condition is more graphically illustrated by computing water content volumetrically as cubic centimeters of water per cubic centimeter of bulk sediment. Expressed in this way, water content is the "effective porosity" of the bulk sediment. Figure 74 shows a plot of "effective porosity" with depth and also the bulk density with depth for core S 334D. It is apparent in this diagram that the specific gravity is increasing with depth while the effective porosity remains essentially constant. The specific gravities of the mineral constituents are essentially the same throughout the length of this core, and it was observed in the field that a distinct stiffening of cores occurred with depth. Evidently the water content remains constant but is using a larger per cent of the available total porosity of the bulk sediment.

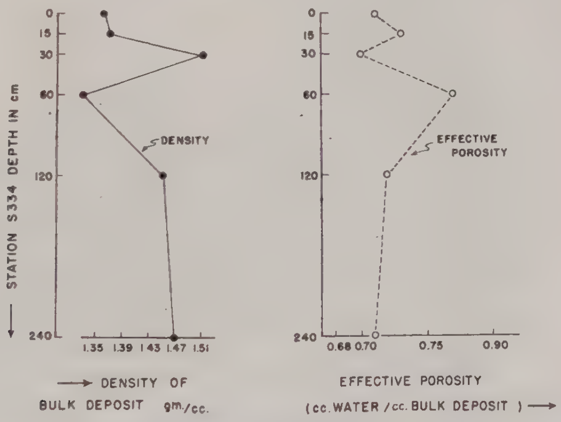


FIG. 74.—Apparently anomalous condition of water content (plotted as cc. water/cc. bulk deposit) which shows no net loss with depth, while density has net increase. Greater utilization of total porosity with increasing depth of burial is suggested as explanation.

A possible explanation of these changes is the compression of organically generated gases within the newly deposited sediment as depth of burial increases. This could lead to increased density with constant volumetric water content. A simple laboratory test for the presence of such gases was conducted in which a randomly selected freshly opened clayey core was placed in a bell jar which was evacuated to a pressure of 22 inches of mercury. After the core had sat at this pressure for about an hour, pockmarks became visible where gas bubbles had worked their way to the surface of the core. In field work, cores containing very abundant gases have been noted on several occasions.

Alteration by organisms.—Tank experiments of the effects of organisms in altering the structures of initial deposits have been discussed under "laboratory studies" (Fig. 13). The importance of living creatures as agents of early diagenesis in natural sedimentary environments can not be overstressed. Without the destructive work of the burrowing organisms the appearance of sediments and sedimentary rock, particularly those deposited in shallow marginal areas, would undoubtedly be quite different. Bramlette and Bradley (1942), in studying North Atlantic deep-sea cores, have stressed the importance of mud-eating scavengers as agents of sediment alteration in their cores. This process has even been considered as an explanation of the infrequence of graded bedding in deep-water sands (Kuenen and Menard, 1952). Studies of the minor structures of the sediments in the Rockport area have shown that burrowing organisms are extremely active in the more saline sections of the bays. Only in the relatively "fresh" waters near the river mouths where few organisms live is there any large-scale preservation of layered structures within the sediments.

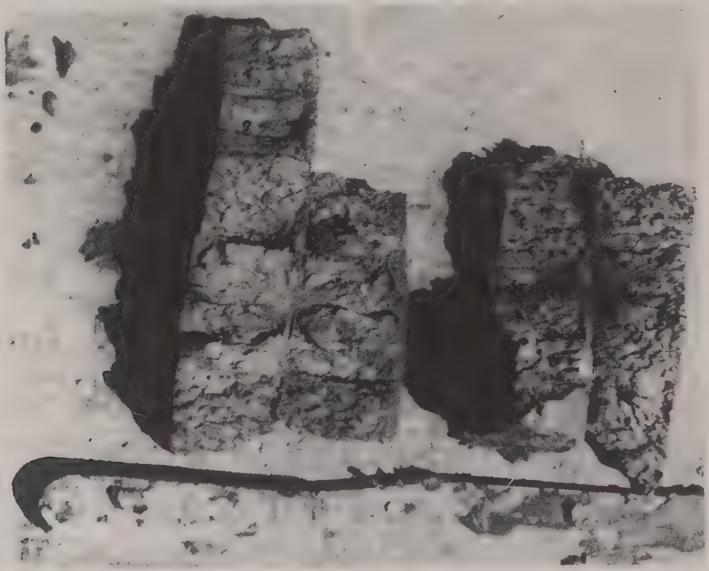


FIG. 75.—Shale-like parting found at 69 feet in San Antonio Bay boring XS 382.

Development of parting planes.—As indicated previously, the sediments obtained in the borings of San Antonio Bay were deposited under similar environmental conditions throughout most of the sections. Along these borings the physical character of the cores changed mainly in becoming increasingly stiff with depth. At about 20 feet the clays could be molded with the hands like modeling clay. At about 50 feet of burial the sediments when bent or twisted were stiff enough to form fractures. At 69 feet the samples had somewhat the appearance of shale (Fig. 75). Definite parting planes were evident and when fractured the clayey sediments showed the blocky step-like appearance of a broken slab of shale. This material was still an unconsolidated plastic sediment, however, and could be molded. It seems significant that the shaly appearance is attained in these recent deposits at a depth of about 69 feet, but further checks should be applied to see if this is significant. Radio-carbon dating of deposits at depths above and below give these deposits at 65 feet an extrapolated age of about −8,500 years.

CHEMICAL CHANGES

At the time of collection of the four 8-foot cores from various Rockport area environments (Fig. 44) careful attention was given to the preservation of the samples for later chemical analysis. In addition, the pH and Eh of the raw sediment were taken immediately after bringing up the cores. The deep borings XG 17, XS 383, and XS 386 were also sampled for chemical analysis, giving a depth coverage of more than 60 feet and representing more than 8,000 years of deposition. The methods of chemical analysis were described under "Laboratory Studies and Techniques."

Interstitial water.—By use of a press and a sintered steel filter the interstitial water from the four 6-foot cores was extracted and titrated for chloride and sulphate ions. Chloride ion concentration in the waters of the bays is definitely variable inasmuch as the salinities may change with seasonal and cyclic rainfall and over longer periods of time with the relative position of the river mouth as it enters the bay. Therefore, the $SO_4^=/Cl^-$ ratio as used by Emery and Rittenberg (1952, p. 789) for studying the California basin cores is not a diagnostic parameter in this environment of shallow restricted bays.

The chloride ion curves by themselves are, however, significant in the bay and river environments in that they show a considerable enrichment of chloride ion in the sediment compared with the overlying water. This enrichment of chloride is particularly high in the river sediments. The fluctuation in amount of Cl^- in the bay environments could be the result of higher salinity conditions in the past but this seems unlikely inasmuch as salinity records show that the present concentrations of chloride in the water are above the average of the recorded years (Fig. 21). There is no continued increase in the chlorinity with depth, however, so that a diagenetic enrichment which continues with depth is not indicated by the near-surface enrichment shown in the curves. In the relatively constant salinity of the open Gulf of Mexico the chloride ion content of the surface sediment shows only a very small increase over that of the overlying water.

Sulphate ion concentration ($SO_4^{=}$) in the waters overlying the sediments of the localities where the four long cores were collected showed a progressive increase with distance away from the river and toward the ocean. This range of sulphate ion concentration is from 0.75 to 3.41 grams per liter as can be seen in the top point in the curves of Figures 70 and 71. Unlike the basin cores discussed by Emery and Rittenberg, however, there is no consistent decrease of sulphate ion with depth. Loss of suphate ions is shown in the San Antonio Bay and offshore cores with depth of burial, but the sediments from the Guadalupe River and Aransas Bay actually increase in sulphate ion content with depth. This is particularly strange in the case of the Aransas Bay core because it is from the only environment in the area which shows reducing conditions within the sediment, as indicated by Eh measurements. If the reducing conditions are the result of the biochemical alteration of sulphate to sulphide then there must be an excess of sulphate. Possibly the sulphate content of the overlying waters in this environment is normally greater than that measured at the time of this collection.

Bulk sediments.—The only chemical measurements of the samples made directly in the field were the electrochemical determination of hydrogen ion concentrations (pH) and the apparent electromagnetic force (Eh) generated by the sediments (Figs. 70–72). These measurements were made directly in the cores by use of a Beckman pH meter and electrodes.

The pH in the upper 240 centimeters of the sedimentary column was found to be relatively constant with depth of burial at any particular environment, there being an average increase of only 0.3 of a pH unit to this depth in the bays and open Gulf. The river sediments decreased 0.35 of a unit in the same interval. Variations in pH with environment, on the other hand, have been shown to amount to about 1 pH unit from the Guadalupe River mouth to the open Gulf (Fig. 44C). Variations with greater depth measured on material collected from borings appear to be more significant. The San Antonio Bay borings, XS 383 and XS 386 show changes of 0.8 pH in 50 feet and 1.1 pH in 58 feet, respectively (Fig. 72). This is an average of 1 pH unit in a depth interval of about 60 feet. The chemistry data extending to 25 feet in boring XG 17 (Guadalupe delta) give a clue of a possible cause for these pH variations. This locality shows an increase in pH as the sediments change with depth from river and delta deposits to those of a bay (Figs. 70 and 72). The changes in XS 386 and XS 383 may be partly the result of the river influence also, since water level during the postglacial rise would cause an up-valley migration of the river mouth and, hence, a vertical increase in river influence near the base of the section. The vertical variations are of a complex nature, however, and are influenced by biochemical alteration which is also an important factor in the determination of the amount of calcium carbonate in the sediments.

Calcium carbonate content of the sediments in the shallow bays, the river, and the open Gulf in the Texas area shows a rather consistent variation with depth of burial. Figures 70–72 show a small increase in carbonate to depths of about 5–10 feet in the short cores, and a general decrease with greater depth in the borings. The initial increase may be the result of precipitation of carbonate from the combination of carbon dioxide formed during early decomposition of organic material. The subsequent decrease in carbonate with depth is somewhat more puzzling. An explanation may be the formation of carbonic acid during the oxidation of organic matter which in turn lowers the pH and results in the solution of carbonate. These explanations are somewhat anomalous, however, in that they account for both an increase and a decrease in carbonate as a result of the alterations of organic matter. Another approach to the problem is in the consideration of the source of much of the carbonate. The Guadalupe River carries a considerable percentage of the total carbonate into the bay environments in the form of finely divided clay sized particles and in solution. The amount of carbonate should then depend on the amount of clay present and the relative influence of the river on the deposit. The curves in Figures 70–72 do not, however, show a positive correlation of carbonate to amount of clay. Increased river influence with depth has been suggested as a possible explanation for the lowering of pH shown in the deep borings, and this greater river influence is not accompanied by increased carbonate content. It must be assumed, therefore, that the diagenetic activities of precipitation and resolution must be important. This conclusion is in contrast to that of Emery and Rittenberg who found a general decrease in carbonate in six of twelve cores from the California basins; one core showed an increase; and the other five were too irregular to allow an interpretation. They concluded that the variations were largely the result of original content at time of deposition.

The Eh of the sediments was determined by using calomel and platinum electrodes inserted directly into the core. Results were recorded in millivolts relative to a standard hydrogen cell. Eh is normally called "redox" or "oxidation reduction potential," and is cited as an indicator of oxidizing or reducing conditions within a sedimentary environment. Readings taken in the Rockport, Texas, area, however, are inconclusive and do not have a consistent correlation with other parameters. Eh readings are difficult to interpret at best in a simple sedimentary system of uniform environmental conditions, because of the complexity of the electrochemical reactions within undisturbed marine sediments. In the shallow-water sediments of the Rockport, Texas, area there are apparently such a variety of forces at work in determining Eh that correlations are not consistent from single readings either with depth or aerially. Eh might be more appropriately called apparent electromagnetic force rather than oxidation-reduction potential. Figures 70 and 71 show the values from cores in four selected environments of the area. A general inverse relationship is apparent in these figures between Eh and pH values. This interdependence of pH and Eh values is well known from studies of simple controllable systems. It is notable that the correlation is not infallible but only general in these complex natural systems. Figure 72 shows the values taken from the deep borings. The inverse relationship with pH is again apparent in parts of XS 383 and XS 386. It is perhaps significant that Eh varies inversely with water content in core XG 17, directly with water content in XS 386, but in core XS 383 no apparent relationship between water content and Eh exists. The only conclusions which can be drawn regarding Eh values is that they are probably not very significant in the light of present knowledge of the chemical and biochemical reactions which occur within shallow-water recent marine deposits. No clear relationship is apparent between depth of burial, or time, and Eh.

Organic carbon content is included in Figures 70–72 principally to show the relatively small variation in this property with depth of burial. In general a small decrease in organic carbon with depth is shown in the deep borings as well as in the more detailed sampling of the shorter cores. Other studies of organic carbon content have shown a correlation of amount of organic carbon to the percentage of clay in the sample. Trask (1932) and Emery and Rittenberg (1952) found this to be true, and soil studies have also in general shown this same relationship. The fact that in many individual Texas coast samples little or no correlation exists between percentage of carbon and percentage of clay may be significant in that it indicates that there is a wider, more evenly distributed range of particulate organic material being supplied to these sediments.

The ratio of ammonia nitrogen (N_{NH_4}) to total nitrogen (N_K) was determined for the raw sediment from the selected chemistry cores and borings. This ratio was designed to detect any decomposition of the nitrogen compounds into ammonia. The plots of the ratio against depth (Figs. 70–72) show very little change in the detailed shallow cores indicating a low rate of decomposition. The deep borings, XS 383 and XS 386, show only a small decrease in the ratio to depths of over 50 feet. The oyster-reef environment which XS 386 passed through shows a strong influence indicating the formation of ammonia, but below the reef environment the ratio drops off sharply to a point below that of the surface figure. These data suggest that there is no uniform rate of decomposition of nitrogen compounds with depth or time, and support the organic carbon data in suggesting relatively slow decomposition of organic matter in the Texas coast sediments.

SUMMARY OF EARLY DIAGENESIS

If the environment of deposition of a sediment is known, it is possible to study vertical variation in chemical and physical properties of this sediment and interpret these changes as diagenesis. Figures 70–72 show these variations determined from studies of shallow cores and deep borings in the Rockport area. The more significant physical changes noted in these studies are the following.

1. Water content of the sediments in the 7–10-foot core showed no uniform decrease with depth of burial but had a strong correlation with the percentage

of clay (Fig. 73). In the deep borings the correlation with clay content continues but a small decrease in water content is general.

2. Specific gravity of the 7–10-foot core varied roughly with the water content but in some cases showed a relative increase with depth. Figure 74 shows the water content and specific gravity data from core S 334D. Water content when plotted as cc. water/cc. bulk deposit shows no net change with depth while specific gravity increases. This suggests that the density of the deposit increases not as a result of water loss but because of increased effective porosity, possibly due to compression of gases.

3. Alteration by organisms is most important in the upper few centimeters of the deposits and is probably the greatest single factor in changing the physical character of newly deposited material.

4. Parting planes develop in the clayey bay sediments at a depth of about 65 feet and an age of approximately −8,500 years. Although still plastic, the sediments showed shale-like features when broken open.

Significant chemical changes are the following.

1. Chloride ion concentration of the interstitial water from the river and bay sediments showed a substantial increase in the upper few centimeters of the core compared with the overlying water. No continued increase in concentration was apparent, however, with increasing depth of burial.

2. Sulphate ion concentration in the interstitial water on the four 7–10-foot cores studied showed no diagnostic decrease with depth.

3. The pH of sediments from the deep borings in San Antonio Bay showed a decrease of 1 pH unit in about 60 feet of burial. This lowering of pH with depth of burial may be in response to a greater influence of the river at the time of deposition.

4. Calcium carbonate content of the sediments shows a net decrease with increasing depth of burial (Fig. 72). This decrease is apparently related to diagenetic processes and is not the result of environment change with depth.

5. Organic carbon and nitrogen data suggest that there is no uniform rate of decomposition of these compounds with depth and that there is a relatively slow rate of decomposition of organic matter with depth in the Texas coast sediments.

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ON QUANTITATIVE BIOLOGY
Volume XX, 1955
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POPULATIONS IN TIME AND SPACE: SYNTHESIS[1]

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Today's subject for discussion was the nature and causes of genetic variability in populations in time and space. It would be certainly impossible to synthesize in a few minutes the problems, techniques and opinions concerning such a broad field. Actually it corresponds to the subject matter of evolutionary studies; any attempt on my part to summarize our knowledge in this field here would prove inane. In connection with the various aspects of our theme that have been touched upon by today's speakers, however, I wish to stress a few points which appear to me of particular significance at the present stage of our inquiry.

1. MORPHOLOGICAL CHANGES

One of population genetics' major aims is that of providing a model sufficient to account for the changes that have occurred in organisms during the past history of our planet. The only record available of these historic processes is that provided by paleontologists and comparative anatomists. This record is in terms of morphology. Yet an exceedingly meager amount of data coming from genetic studies is available to explain morphological changes in time. The sort of morphological changes that we find fixed in the fossil record has been the product of natural selection acting on very complex polygenic systems. The very fact of observing certain changes indicates that successive stages of these time processes had definite survival values. We observe transformations in size and shape of hard parts of animals, in the fossil remains. When these transformations have not led to blind alleys or to extinction of an evolutionary line, they must have been positively correlated with an increasing fitness with respect to the temporal environmental conditions. The succession of forms that we observe in rocks differs thus from results that the breeder obtains in his experiments in an important respect. While the changes produced by selectionists in domestic animals and in cultivated plants seldom coincide with an increase in the fitness of the organism, those produced by natural selection are a part of fitness, they are in fact a *visible* component of fitness. On the basis of present knowledge we must conclude that the morphological changes observed in fossils are the product of transformations in the whole genotype of the organism.

Since it is not possible to perform genetic experiments with corpses an indirect way out of this otherwise inevitable impasse is that of analyzing changes in space that similarly have an adaptive value. In this respect, the data here presented by Prevosti on morphological clines in *Drosophila subobscura* populations seem of particular interest. Not only was a cline of size demonstrated in correlation with temperature gradients prevailing in Europe, but it was shown that the observed differences are genetically determined. Furthermore, artificial selection for size has produced parallel results, though different in absolute values, when the experiments were carried out on samples taken from two populations that differed in their mean size. Moreover, the correlated response for other traits indicates the diversity of gene constellations present in wild populations. Evidence of this type is certainly very useful for an understanding of our problem, but it seems to me that if we intend to explain evolutionary transformations we should attempt a more direct attack. Greater stress, I think, should be laid on laboratory experiments in which natural selection would bring about measurable morphological change over a limited number of generations. Some data derived from *Drosophila melanogaster* populations, that I have studied in the past few years, show that it is possible to observe remarkable changes over a relatively short period of time. For example, in the course of 55 generations a change has taken place in the size of the wings, and its rate was of 1/20,000 of the standard derivation of its original mean per generation. This is a rate of the same order of magnitude as that of the fastest evolutionary change heretofore recorded, namely the length/height index of the human skull (Buzzati-Traverso, 1955a). Similar observations were made on other populations. The genetic explanation of the adaptive value of morphological traits is, I think, a central problem for evolutionary studies and we are enough advanced to tackle it.

2. POPULATION'S FITNESS

Directly connected with the problems discussed by Carson, Prevosti and Nicholson is that of the fitness of a population. During the past few years population geneticists have become increasingly aware of the problem of evaluating the fitness of a population. Several observations were made that can be accounted for only by assuming that natural selection is acting also at a level above the individual. We have heard here a theoretical discussion by Professor Sewall Wright of the value V_E, that is of the "external selective value of the gene frequency system." This can be considered at three different levels, (1) growth of the population, (2) interdemic selection, and (3) invasive capacity of the population. The problem that we are facing is that of measuring such value. While it is possible to visualize at a theoretical level how one population could have a fitness higher than that of another population of the same species, it appears rather difficult to identify and measure such difference. In concrete terms, we should compare two populations with respect to each other assuming identity of environment. Now, in which way could one population be superior to the other? The superiority in fitness might mean that one exploits better the available space and energy sources. This being the case, one could perhaps measure the fitness of a population in terms of the ability of a certain group of organisms to transform whatever food and energy is available into a larger bulk of living matter of its kind. Disregarding the time parameter, that is, assuming that for a particular comparison we would take measurements over identical periods of time for the two populations under analysis, it would be possible to obtain a so-to-say absolute measure of fitness by evaluating the total mass produced in that time interval. This would boil down, then, to a mere problem of counting and weighing the individuals that have saturated a certain environment. In some experiments of mine with artificial populations of *Drosophila melanogaster* this is actually what happened (Buzzati-Traverso, 1955b). The populations were kept for many generations in constant environmental conditions, with a fixed amount of space and food. Natural selection acting upon these genetically heterogeneous populations produced a new average genotype which was able to transform the constant available food source into a larger mass of *Drosophila* material than the original genotype could do at the beginning of the experiment. Even though these results were obtained from an experiment which was primarily designed for analyzing a different problem, they clearly indicate that it is possible to carry out this type of measurement of total fitness of a population. While this might be feasible under the simplified conditions of the experiment, it is hardly conceivable that one might carry out similar measurements on natural populations whose total size can almost never be determined and where the majority of the environmental factors are unknown. I am far from convinced that this type of approach is meaningful for our evolutionary studies, but it might be worth while to explore its merits. What we are dealing with at this level is the intrinsic ability of living matter to grow, multiply and occupy whatever space is available, transforming energy sources into a larger amount of mass of its kind. The efficiency of such transformation falls certainly within the control of the genotype. All sorts of physiological mechanisms are involved in this energy transformation and these, too, are genetically controlled. It might be, therefore, worthwhile investigating in some detail both at the theoretical and at the experimental level how natural selection may control these aspects of fitness. An interesting corollary of this approach is that in any population the intensity of natural selection will be steadily increasing, even under supposedly constant environmental conditions. At any particular time the population will be better adjusted to its environment than at any previous moment. As a result of the change in the genotype the environment will be different too. No such thing as a constant environment could therefore exist; natural selection will thus become increasingly stringent.

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[1] Contribution from the Scripps Institution of Oceanography, New Series, No. 800.

3. Population Waves

One other important aspect of problems of populations in time and space was brought to our attention by the very interesting data of Carson. Under natural conditions the size of a population cannot be stable over any appreciable period of time. Fluctuations in numbers are known for every species that has been studied quantitively in the field; similarly it is known that the distribution range of a species varies with time. Carson has shown that *Drosophila robusta* occupies, with a remarkable amount of stability, a certain area and that at the margin of the distribution subsidiary populations are formed, which may survive in the newly occupied territory for shorter or longer periods. The picture of the present distribution of elms and *Drosophila robusta* in North America, that Dr. Carson showed us, reminded me very much of the semi-diagrammatic figure that Timofeeff-Ressovsky (1940) used to illustrate what he called "population waves." This author at that time examined the consequences of accidental fluctuation in numbers and of the ensuing establishment of temporary populations on variations in gene frequencies. Carson has studied directly in the field another aspect, namely that of the concentration of chromosome inversions in central and marginal populations and the ensuing differences in the "index of free crossing over." It appears to me of particular significance that not only did peripheral populations show a higher index of free crossing over but that the specific homozygous gene arrangements, that one finds prevailing in different marginal areas, are different. Here we have indeed a very interesting example of evolutionary experiments carried out by the species *Drosophila robusta* at the margin of its distribution. Different "evolutionary candidates" are produced at the same time at different places and possibly at different times at the same place. These findings can be compared to those of Vavilov (1927) where he described the occurrence of homozygous recessive mutants in marginal populations within the distribution area of the progenitors of cultivated plants. The trend from higher heterozygosis of the central part of the distribution of the species to the lower heterozygosis at its periphery may indicate an interesting evolutionary mechanism. A condition of balanced polymorphism, whether of single gene mutation or of gene arrangements, might be correlated with a phase of stabilizing selection. When, on the other hand, a species enters a phase of more rapid evolution an increase in homozygosis takes place with the fixation of the genetic conditions that are particularly adapted to the new environment. The data presented by Dr. E. B. Ford, in this Symposium, for industrial melanism, are probably examples of such tendencies.

4. MUTATION RATE

In the discussion of the genetic structure of populations in time and space, probably something more should be said than has been the case today for the significance of mutation as an evolutionary factor. Recent work of Scossiroli (1954), Clayton and Robertson (1955), Buzzati-Traverso (1954), shows that, at least under experimental conditions, an increased mutation rate may be of significance for bringing about a more rapid change under artificial or natural selection. The traits studied in these experiments were controlled by many genes and it is precisely on the significance of mutation as a factor for the evolution of polygenic traits that I wish to attract your attention. The experimental evidence on the subject, limited as it is, seems to indicate that theoretical conclusions according to which an increase in mutation rate is detrimental to a population, are not substantiated when one considers the whole genotype. At this moment, therefore, I think it would be very important if more work could be carried out in order to evaluate the relative significance of mutation rate, population size, recombination frequency and intensity of selection on changes produced on traits controlled by many genes. It could well be that the same mutation pressure might bring about very different results, under identical selection pressures, in relatively large and small populations. The same mutation which is detrimental in a certain genetic milieu could have a positive selective value in a different genetic milieu. Thus, new genetic variability could encounter different fates in populations of different size as a result of the different chances it would have of combining with the proper constellation of genes. To test these possibilities experimentally one should probably work with a relatively large number of individuals. In view of the laboriousness of selection programs on quantitative traits it will be necessary to design experiments where artificial selection is carried out on physiological traits, or on self selecting components of fitness under natural selection.

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Geochimica et Cosmochimica Acta, 1955. Vol. 8, pp. 53 to 62. Pergamon Press Ltd., London

The normal distribution in geochemistry*

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(*Received* 12 *May* 1955)

ABSTRACT

The proposed geochemical law of Ahrens, that elements are distributed log-normally in igneous rocks, is critically examined. It is concluded that existing data do not confirm this proposition or suggest any extension of it. The application of statistics to geochemistry is formulated under the topics of (1) description of results and (2) statistical prediction. Meaningful interpretations of frequency distributions in nature are dependent upon a knowledge of the factors involved in the formation of the geological system under study, and a knowledge of the contribution of laboratory and field sampling errors to the numerical data.

Introduction

In the past year two stimulating papers (Ahrens, 1954a; Shaw and Bankier, 1954) have appeared in which the application of statistical methods to geochemistry are discussed.† In both of these papers the assumption of a normal distribution plays an important role. Frequency distributions of elements have been of primary importance in the consideration of geochemical abundances, and Ahrens (*loc. cit.*) has proposed a fundamental law of geochemistry: *the concentration of an element is log-normally distributed in a specific igneous rock.* He has suggested that this law may be extended by frequency distribution studies of other rock types. The purpose of the present investigation is to examine the proposition of Ahrens and to discuss the role of the normal distribution function for elements in nature. These propositions have recently been discussed in a limited sense by K. V. Aubrey (1954).

Discussion of Ahrens's Proposition

The published evidence for Ahrens's proposal consists of twenty frequency distributions of various elements in granites and diabases. A set of histograms were drawn in which the frequency distribution of a given element is displayed where the abscissa is divided into arbitrary intervals in units of p.p.m., and the ordinate gives the frequency of individual analyses whose results fall in a particular p.p.m. interval. This histogram is accompanied by a second in which the individual entries are the logs of the entries. The graphs purport to show that a log-transformation usually results in a normal distribution. Ahrens, on the basis of the above, then proposes his Fundamental Law of Geochemistry.

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* Contribution of the University of California, Scripps Institution of Oceanography New Series No. 801. This work was sponsored in part by the Office of Naval Research under contract with the University of California.

† More recently Chayes (1954) has published a critical note on Ahrens's paper. Ahrens (1954b) has published a sequel to his original paper with further discussion in support of his earlier propositions. The present writers' work was completed independently and prior to the appearance of these two papers.

Visual examination of the graphs show that in many cases there is an undoubted tendency towards increase of symmetry of the histogram by using the log-transform. In other cases, however, no increase in symmetry or decrease in subsidiary peaks is visually apparent after use of the log-transform. The following points occurred to the writers:

(a) Histograms are often misleading. A slight change in the arbitrarily selected class interval may give an entirely different apparent shape to the histogram.

(b) Symmetry is not in itself a property solely possessed by the normal distribution.

(c) The sample sizes in every case small for purposes of determining the form of the frequency distribution. The sample sizes range from about 25 to 60. For example, if it is desired to test goodness of fit of a sample cumulative curve to a hypothetical curve whose parameters are specified in advance (in this case normal or log-normal), one procedure is to compute a percentage-error strip based on the theoretical curve. If the sample cumulative curve is outside this band at any point, the theoretical curve is rejected. The width of this band is determined in advance by the percentage-error one is willing to accept. The following figures, computed by the writers, illustrate sample sizes necessary for a given error band.

Interval or error band = 10 per cent.

Risk of being wrong by rejecting curve if outside of band	Minimum sample size required
0·01	1037 approx.
0·05	739 ,,
0·10	600 ,,

The reader interested in computing sample size required for other "error bands" at various levels of risk is referred to DIXON and MASSEY (1951, p. 257). Testing whether a sample comes from a normal distribution with parameters unspecified is more difficult, and minimum sample sizes would probably be still larger than the values given here.

In view of the preceding, the writers applied a simple graphical test to the data as given by AHRENS. The test involved plotting the cumulative frequencies on a special graph paper which is so designed that a normal or log-normal frequency distribution will plot as a straight line. The cumulative form of the frequency distribution has the advantage (for graphical analysis) of being independent of the arbitrary choice of class interval. Marked departure from a straight line indicates the distribution is not normal.*

The plots were made on the two kinds of paper for normal and log-normal

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* The technique of testing goodness-of-fit by the use of Normal-Probability paper is described in detail in DIXON and MASSEY (1951) pp. 55-59. Normal and log-normal paper can be obtained from the Codex Book Co. Inc., Norwood, Mass. This test was used instead of Chi-square or Kolmogorov-Smirnov tests, (MILLER, R. L., and OLSON, E. R., in press), because of rapidity and ease in use.

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distributions respectively. Due to the small sample sizes, the writers took the point of view that the test would not precisely indicate the existence of a normal or log-normal distribution, but would reliably show such cases where normal or log-normal were not correct inferences from the sample data. Table 1 gives the results of the graphic analysis of Ahrens's data. Six of the twenty sets of analyses are possibly log-normal, two of the twenty are possibly arithmetic-normal, and ten are neither log- nor arithmetic-normal. The remaining two are not in a form suitable for testing. We can only conclude that Ahrens's proposal is not justified by the data he presents.

Table 1

	Canadian granite	*Ontario diabase*	*New England granite*
Ga	*U**	?	
Sc	log-normal possible	arithmetic normal possible	
K	*U*	*U*	*U*
Rb		*U*	arithmetic normal possible
Co		*U*	
Zr	*U*	*U*	
V	log-normal possible	*U*	
La	*U*		
F	log-normal possible in Canadian and New England granites together.		
Ce	*U*		
Mo	log-normal possible in unnamed granites		
Pb	log-normal possible		
Cr	log-normal possible		

* *U* indicates neither a normal or log-normal distribution was found.

Table 2 gives the results of further investigations by using the previously described graphic method on other published data, and on deep-sea sediment analyses of E. Goldberg and G. Arrhenius (unpublished). Again, the results do not confirm the proposed "Geochemical Law" or suggest any extensions of it.

Application of Statistics to Geochemistry

In general terms, application of statistics to geochemistry may be formulated under two main topics: description, and statistical inference or prediction (e.g., Crámer and Shaw, *loc. cit.*).

Table 2. Further analyses of frequency distributions of elements in nature by use of normal and log-normal probability paper.

Element	*Reference*	*Result*
Cu in coal	AUBREY, 1954	possible log-normal
Zn in granites	LUNDEGÅRDH, 1949	U*
Ca in Fe meteorites	UREY, 1953	possible log-normal
Na in Fe meteorites	do. do.	possible log-normal
Si in Fe meteorites	do. do.	U
Mg in Fe meteorites	do. do.	U
Al in Fe meteorites	do. do.	U
Ni in Fe meteorites	GOLDBERG *et al.*, 1951	U
Co in Fe meteorites	do. do.	U
Au in Fe meteorites	do. do.	U
Pd in Fe meteorites	do. do.	U
Ga in Fe meteorites	do. do.	U
Mg in glauconite	HENDRICKS and ROSS, 1941	U
Ca in glauconite	do. do.	U
Na in glauconite	do. do.	U
K in glauconite	do. do.	U
Al_2O_3 in glauconite	do. do.	U
SiO_2 in glauconite	do. do.	U
Mno/NiO in pelagic sediments	GOLDBERG and ARRHENIUS (unpublished)	U
NiO in pelagic sediments	do. do.	U
MnO in pelagic sediments	do. do.	U
Ti in deep sea core 49BP	do. do.	possible arithmetic normal
K in deep sea core 49BP	do. do.	possible log-normal
Ti in deep sea core 50BP	do. do.	U
Mo in basalt and diabase	KURODA and SANDELL, 1954	U
Mo in intermediate rocks	do. do.	U
Mo in granite	do. do.	possible log-normal
Mo in silicic volcanics	do. do.	U
K_2O in granites (all granites in world analyzed between 1884-1913)	WASHINGTON, 1917	possible arithmetic normal

* *U* indicates neither a normal nor log-normal was found.

Description. Large sets of numbers, cumbersome and difficult to interpret, may be reduced to a useful form by the use of descriptive statistics. The average value, an expression of the degree of variation around the average and graphical representations of frequency distributions, are of obvious usefulness.

Statistical inference or prediction. Statistical inference goes beyond the problem of refining or condensing large masses of numerical data. Subjective inference, from a sample to a much larger collection from which the sample is drawn, is common and widespread. Statistical inference is a formalization of this procedure. For example, it is sometimes possible to state with preassigned confidence a range or interval which will include some parameter of a large collection (e.g., the mean) on the basis of a relatively small sample. This is legitimate, provided the required mathematical assumptions are satisfied. These usually, but not always, involve, among others, the form of the frequency distribution.

The application of frequency distributions in statistical inference can be summarized in the following way:

A. The form of frequency distribution function of the fundamental set (total collection or statistical universe) is known, at least approximately.

1. If the frequency distribution is normal, a large number of statistical tests can be performed, many of them by use of tabulated functions.
2. If the frequency distribution is not normal but is of known form, a suitable transformation can often be made, so that the new set of values will be normally distributed. One may then proceed as above. For example, the logarithms of numerical results are sometimes normally distributed.

B. The frequency distribution function of the set is not known.

1. Non-parametric tests (distribution free methods) may be used for statistical inference, if the form of frequency function is not known, or one is not willing to assume its form.

The normal distribution has been emphasized in the development and application of mathematical statistics. This is due to both mathematical convenience and observational results. Many of the mathematical problems involved in the development of procedures for the utilization of statistical inference are greatly simplified if the unknown distribution is considered to be normal. Further, the central limit theorem, fundamental to mathematical statistics, states that under very general restrictions the sum of n independent variables is asymptotically normally distributed, whatever the distributions of the n independent variables may be. In several fields of science such as paleontology, biology, and physics, normal or asymptotically normal distributions have been found. In such studies the universes are often clearly defined (see below).

In geochemistry no models have yet been proposed to account for normal frequency distributions of chemical elements. The authors attempted to set up two types of models, and to test them against field or theoretical data. The first involved the Central Limit Theorem, in which a log-normal distribution arises under assumptions which appear plausible in a natural system (e.g., in which geological processes are at work). This schematization was first proposed by CRÁMER (1946, pp. 219-20). A second model was based on the "Law of Errors" interpretation of the normal distribution with regard to the influence of errors upon the field or laboratory techniques. The normal distribution was first described by GAUSS and by LAPLACE. A derivation given in LEVY and ROTH (1936) is used by the writers (see Appendix A).

Both models failed to reflect natural situations that were conceived by the authors, although they appeared to be most flexible in their application. This of course does not mean that either model cannot work in a geochemical context.

An important consideration in this discussion is the concept of a statistical universe. In very general terms this involves a collection of objects which have in common some measurable property. The frequency distribution represents the way that various values of the measurable property are distributed within this universe.

Let us consider the phosphorus content of quartz samples, which constitute a collection of objects. It is first necessary to examine the limits of our "universe." Shall we consider both the high- and low-temperature quartz? Shall we confine the collection only to the North American continent? Shall we consider the phosphorous only included as apatite? Considerations of this sort should be made before any statistical analysis is attempted.

An illustration of the importance of the above can be found in such a simple procedure as comparing two sample averages. If the population variances are known (or even unknown) and are assumed equal, then a particular test is available. Following this mechanical procedure, one arrives at an answer which states, e.g., "sample results like the ones observed are probable if the two population means are equal, and improbable if they differ by more than a certain amount."

In the above case, it is clear that some knowledge or intuitive ideas of the population, in terms which are meaningful to the problem, should be available if clear interpretations of results are to be gained.

Unless such precautions are taken, there is a real danger of losing sight of the original problem by mechanically using formal and often complicated statistical procedures.

CONCLUSION

An alternative view to that held by AHRENS is advanced on the basis of the preceding considerations. It appears to the writers that the elements in geochemical universes are not all distributed as log-normal or as any other single function.* The complexities of the situation in terms of both chemical and geologic time concepts lead to the following proposition:

A more realistic expectation is that different population frequency distributions exist for separate groups of one or more elements with respect to various rock types or mineral suites. In particular, the distribution of an element in a single rock type may differ from the distribution of the same element in another rock type of some general classification such as igneous rocks. The frequency distribution of any element is postulated to be a function of the following interdependent factors:

1. Chemical environment of formation or deposition.
2. The nature and number of elements involved in the rock type or mineral suite.
3. Geologic time considerations.
4. The reversibility or irreversibility of the chemical reactions.

For example, one may consider the possibility that a particular element may have a characteristic frequency distribution in a certain rock type or mineral, but may change with time (e.g., diagenesis) from one rock type to another. An example of this is (a) nickel in siderite, vs. (b) nickel in pelagic sediments.

However, one should first consider the nature of the universe that is being sampled. Further, an evaluation of the *a priori* knowledge of the particular time-dependent chemical system is necessary before widespread sampling and analysis of frequency distributions is attempted. A major difficulty must be considered in a study of this sort. The numerical data are the result of two sets of factors, the first composed of laboratory and field sampling errors, the second of contributions by factors involved in the formation and stability of the particular rock type studied.* Unless the influence of these two sets of factors can be distinguished, the writers do not feel that meaningful interpretations of frequency distributions of elements in geochemical systems can be made.

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* In fact, it should be made clear that great difficulties are involved in showing that any set of empirical data is *precisely* described by a specific function. Thus the search for specific functions to describe universes in nature seems fruitless. On the other hand, if a universe is *approximately* described by a particular function, statements of prediction and comparison can be made. Herein lies the usefulness of such investigations! Even here it is possible that, for certain purposes, several functions will serve equally well.

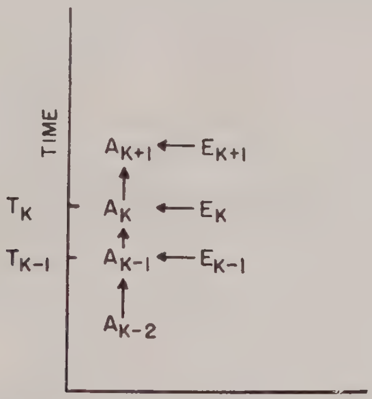

Fig. 1. Graphical representation of the Crámer model. E is an impulse acting upon A_k at time t_k. E_k is interpreted by the writers to be the total impulse composed of all the forces operating on A_k at time t_k.

We thus doubt the value of a statistical examination of empirical data in the absence of a meaningful hypothesis, and with no attempt to define the universe or universes which are being sampled. We believe that in such cases a model or analogue should be erected, drawing from both theory and known field relationships for its construction. In this context, statistics would be useful in testing those parts of the model where the parameters are unknown, but empirical data are available.

APPENDIX A

The following arguments paraphrase Crámer's discussion. Consider an individual measure A such as the amount of a chemical element in given rock (e.g., zirconium in a diabase). This measure A takes on various values over a time sequence t_0 to t_N. The Crámer model is schematically pictured in Fig. 1. The E_k are considered to be "independent random variables," and it can be seen above that the value of A at time t_k is the result of the total impulse E_k and the value of A at the previous time $t_k - 1$. The following equation states the situation:

$$A_{k+1} = A_K + E_{k+1}\, G(A_k)$$

where $G(A_k)$ is some function of the value of A at previous time t_k.

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* For example, there is considerable published work on experiments designed specifically to evaluate errors of measurement (i.e., evaluation of results and design of procedure by analysis-of-variance techniques). The way the field samples are collected and handled is also of primary importance in a study of this sort. There is available an extensive literature on statistical sampling techniques, some of which may be reasonably adapted to the field-sampling aspects of the problem. Youden (1951) from a chemical point of view, Cochran (1953) for sampling, and Krumbein and Miller (1953) for a summary of work in geology, are suggested, for further reading.

The successive values of A are thus put into cumulative form as illustrated by Fig. 2, where

$$A_{k+1} - A_k = E_{k+1}\, G(A_k)$$

and

$$E_1 + E_2 + \ldots + E_n = \sum_{0}^{n-1} \frac{A_{k+1} - A_k}{G(A_k)}$$

If the E_i's are small and n is very large,

$$E_1 + E_2 + \ldots + E_n = \int_{A_0}^{A} \frac{dt}{G(t)}.$$

The Central Limit Theorem (Crámer, 1946, p. 214) states (with mathematical conditions satisfied) that whatever the distribution of the independent variables E_i, the sum $E = E_1 + E_2 + E_3 + \ldots + E_n$, is asymptotically normal. Cramer in his model has thus developed the relation $E = \int_{A_0}^{A} \frac{dt}{G(t)}$, and states that the various values of this integral are normally distributed.

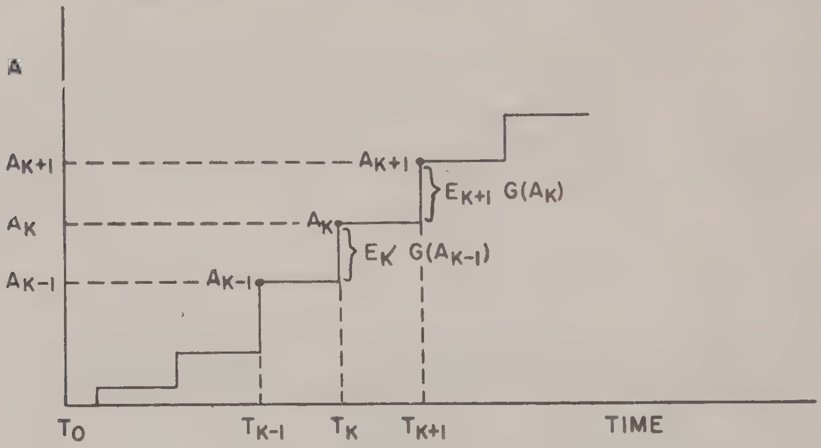

Fig. 2. The values of A as a function of time as influenced by the impulses E_i.

If $G(t) = t$ (the effect of each impulse directly proportional to A_k), then $\int_{A_0}^{A} \frac{dt}{G(t)}$ becomes $\int_{A_0}^{A} \frac{dt}{t}$, and log A is normally distributed, giving a log-normal distribution, the form referred to by Ahrens.

The mathematical assumptions are: (a) E_n and E_i are independent random variables; (b) their number is large and the effect of any one is small; (c) the mean and standard deviation are finite; and (d) the third moment about the mean exists.

Several possibilities for utilizing such a model as a reasonable explanation of the normal or log-normal distribution of elements in nature are discussed below.

The difficulties in the prediction of element distributions in a particular set or universe become evident upon examination of the processes that give rise to a set or universe consideration. Let us consider a major geological process, accumulation of deep-sea sediments. The chemical composition of the oceans is fairly uniform.

In the formation of a pelagic sediment we are concerned both with the genetic components originally building up the deposits, and with changes taking place after deposition. We shall concern ourselves solely with the former process. Here, each addition of a component may be considered as an impulse E_k. As an example, the nickel of pelagic clays probably arises from two sources, the lithosphere and precipitation processes in the ocean (GOLDBERG, 1954). Although the frequency distribution of nickel in the hydrogenous component (manganese oxides) and in the lithogenous component (including pyroclastics) may each be normally distributed, a mixture of the two as found in nature may not be. The observed frequency distribution of nickel in pelagic sediments is not normal, and may reflect the above hypothesis.

CRÁMER states that the sequency of impulses, $E_1 \ldots, E_n$, are to be considered random variables. Thus the probability that any impulse E_n takes on a certain value (has a certain directed effect in our context) is not in any way influenced by the values assumed by the previous $n-1$ impulses. Therefore, the distribution of the random variable E_n is independent of any hypothesis made with respect to the value assumed by the combined variable $(E_1 \ldots E_{n-1})$, so that E_n and $(E_1 \ldots E_{n-1})$ are independent.* In the case of the pelagic sediments, an example of a meaningful set of E_i's would be that of total environmental effect on element A at various instants in time, during deposition and also after deposition right up to the time the deposit is analyzed. In our context, the total environment previous to time E_n thus should have no effect on the value taken by E_n. This requirement of independence does not seem to satisfy the situation as it exists in nature.

It is not our purpose, however, to discuss the merits of the model described above, but to illustrate how the use of the Central Limit Theorem in a model may lead to a reasonable expectation of the normal or log-normal distribution for an element.

A derivation of the normal distribution which is not dependent on the Central Limit Theorem is given in LEVY and ROTH (1936), pp. 118–120; see also LINDSAY (1941), p. 35, and LINDSAY and MARGENAU (1936), pp. 181-187. In this case it is required to visualize a natural situation where a variable x (such as amount of an element in p.p.m.), varies about a mean value a in such a way that the individual variations are independent of one another. The most frequent value corresponds to the average value, and the range of values of the deviations is $-\infty$ to $+\infty$. The infinite range is obviously impossible for an element in p.p.m., but is introduced for mathematical simplicity (see, for example, LINDSAY (1941), p. 35).

The assumptions include;

(1) The deviations $\xi_i = (x_i - a)$ are independent of one another;
(2) P, a function of $\xi_1\xi_2 \ldots \xi_n$ and of a, is continuous and differentiable over the entire range (which is from $-\infty$ to ∞);
(3) There is a single greatest value of P in the range of the variable;
(4) The value of a which makes P a maximum is the average value.

The above-mentioned derivation and the assumptions which underlie it seem to the writers to best fit a situation in geochemistry where experimental errors form a distribution about some "true" analytical value.

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Dissolved organic matter in the sea*

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We have little real information about the nature and amount of dissolved organic matter in the sea, especially in deep water. Among the few recorded determinations of dissolved organic carbon the limited number made by Krogh (1934) have seemed to us to be perhaps the most reliable. We are but slightly better off in our knowledge about dissolved organic nitrogen. In addition to a few determinations made by Krogh (1934), some results reported by von Brand and Rakestraw (1941), using the same methods, may perhaps be regarded with confidence. On the basis of these limited data it would appear that the concentration of dissolved organic matter in the open sea is fairly constant at about 5 mg per litre.

Krogh's work, just referred to, was carried out with the extreme care and attention to detail which was characteristic of all his microchemical analyses, but because of its limited extent (his carbon results were obtained from six samples collected from a single station) it has long seemed to us highly necessary to corroborate and extend it. His methods have never been used again until very recently, when Kay (1954) used a modification to obtain results in the shallow waters of the Kielerbucht.

Accordingly, in the spring of 1953, we assembled apparatus essentially similar to Krogh's and carried out the analyses shown in Table I, on samples from three stations off the coast of Southern and Lower California. The results are shown graphically in Figure 1, along with curves for temperature and for oxygen at Station 110.70. Two important conclusions emerge:

The general level of concentration of dissolved organic carbon which Krogh reported (two to three milligrams per litre) was confirmed at these stations. However, instead of being homogeneously distributed it is definitely less at intermediate depths. The significance of this fact is not clear; the data are too limited to conclude that it is related to the location of the oxygen-poor layer. In any event, it throws some doubt upon certain of Krogh's conclusions.

In the fall of 1953, samples were obtained from two stations on the " Transpac " expedition in the north-western Pacific. The results from these are tabulated in Table II and graphically shown in Fig. 1. It will be seen that these are rather more irregular in the upper layers and that the general level of concentration is distinctly lower than at the earlier stations. All samples except that from 506 m at Station T-P 99 were analyzed in duplicate. The samples from these two stations were frozen immediately and kept in this condition until analyzed several months later. While this introduces some uncertainty it nevertheless seems unlikely that significant oxidation took place in the meantime. Deep-sea water has been preserved for much longer times and at higher temperatures without appreciable consumption of oxygen (Rakestraw 1947). Keys, Christensen and Krogh (1935) have also shown that the dissolved organic

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* Contribution of the Scripps Institution of Oceanography, New Series No. 802.

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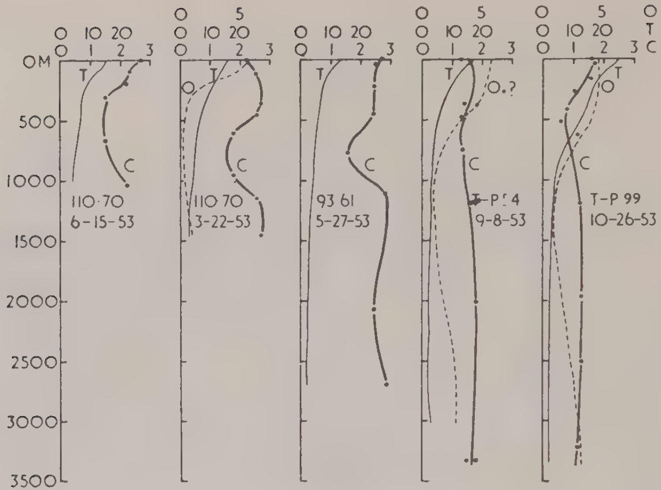

Fig. 1. Vertical distribution of dissolved organic carbon at two stations off the California coast (110.70 and 93.61) and two in the north-western Pacific (T-P 54 and T-P 99). Curves show carbon in mg/L (C), temperature ° C (T) and dissolved oxygen ml/*L* (O).

Table I.—Vertical distribution of dissolved organic carbon

Station	*Location*	*Date*	*Depth (m)*	*Carbon (mg/L)*	*Temp. ° C*	*Dissolved oxygen (ml/L)*
110.70	28° 40′ N 118° 20′ W	6/15/53	0	2·68	16·14	
			99	2·30	13·51	
			195	2·20	9·65	
			317	1·50	8·16	
			665	1·49	5·55	
			1043	2·27	3·93	
110.70	,,	3/22/53	0	2·14	15·62	5·53
			104	2·58	13·96	5·17
			381	2·73	7·78	0·72
			470	2·59	6·90	0·43
			566	1·92	6·22	0·33
			759	1·41	5·09	0·32
			955	1·71	4·23	0·52
			1147	2·58	3·66	0·74
			1487	2·73	2·96	1·10
93.61	32° 50′ N. 119° 45′ W	5/27/53	0	2·67	14·36	
			32	2·48	12·94	
			235	2·43	7·73	
			446	2·49	6·12	
			767	1·52	4·59	
			1092	2·76	3·69	
			2077	2·31	2·02	
			2690	2·82	1·73	
100.90	29° 45′ N 120° 50′ W	4/28/53	3000	2·50	—	

matter is very resistant to bacterial action and does not change significantly during storage of water.

We are unable to find any other systematic analytical error which would account for such a large difference in the average concentration in the deep water. On the other hand, it is difficult to explain such a difference, since the phosphate concentration, for example, is approximately the same in the regions concerned. The dissolved organic carbon, although in lower concentration at all depths, is not uniformly distributed vertically, being less in the intermediate zone, as it was in the eastern Pacific. In this case, however, the zone of lower carbon concentration seems to be somewhat above the steep oxygen gradient.

It is important that we learn more about the dissolved organic matter, since it is the largest fraction of the total organic matter in the sea. Although for the most part it seems to be resistant and unreactive we do not know what relation it has to the " oxidizable organic matter " which plays an important part in the distribution of dissolved oxygen. The work reported here will be continued and extended.

Table II.—Vertical distribution of dissolved organic carbon

Station	*Location*	*Date*	*Depth (m)*	*Carbon (mg/L)*	*Temp. (° C)*	*Dissolved oxygen (ml/L)*
T-P 54	40° 34′ N 170° 2′ E	9/8/53	0	1·29	19·2	5·67
			10	1·66	19·0	5·34
			273	2·72	8·9	4·94
			366	1·42	7·0	4·56
			371	1·87	7·0	4·54
			464	1·47	5·8	3·70
			469	1·34	5·7	3·68
			753	1·37	4·3	1·35
			758	1·37	4·3	1·37
			2020	1·78	2·4	1·87
			3340	1·80	1·9	3·40
			3345	1·48	1·9	3·40
T-P 99	31° 55′ N 142° 12′ E	10/26/53	0	1·57	25·4	4·58
			24	1·72	25·0	4·56
			153	1·57	19·2	4·41
			257	1·03	17·1	4·61
			406	0·78	15·3	4·21
			506	0·59	12·9	3·96
			607	1·18	10·3	3·65
			803	0·88	6·3	2·24
			1190	1·27	3·7	0·94
			1995	1·27	2·3	1·76
			2504	1·27	2·1	2·34
			3220	1·12	1·9	3·03
			4177	1·08	1·9	3·44
			5254	0·98	1·9	3·67
			6290	1·18	1·9	3·71

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Printed in England by Page Bros. (Norwich) Ltd.

Papers in Marine Biology and Oceanography, pp. 204-211. Pergamon Press Ltd., London.

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Distribution of planktonic Foraminifera in some Mediterranean sediments*

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Summary—The planktonic foraminiferal populations of the Mediterranean Sea may be differentiated from those of the adjacent Atlantic Ocean.

Three distinct populations are found located in the western and eastern Mediterranean and the Aegean Sea, and additional discrete populations may occur in the unsampled areas.

Populations probably are derived from the Atlantic and from indigenous ancestral stock.

The direction of coiling of *Globorotalia truncatulinoides* shows a shift to left coiling dominance within the Mediterranean. Additional statistical analysis may give further evidence concerning derivation of species in the area.

INTRODUCTION

THE PLANKTONIC Foraminifera in sediment-surface samples from forty-six stations throughout the Mediterranean Sea have been studied and compared with planktonic assemblages in the adjacent Atlantic. These populations show some regional variation and the Mediterranean faunas as a whole differ from those of the Atlantic. The samples were collected, in 1947–48, by members of the Woods Hole Oceanographic Institution on R/V *Atlantis* Cruise 151. This study was supported by the Office of Naval Research (Project NR 081-050, Contract Nonr—233 Task 1). The drafting was done by Miss J. F. PEIRSON and R. R. LANKFORD.

Much has been published on the description and taxonomy of Mediterranean faunas but few quantitative studies have been made. PHLEGER (1947) gives quantitative lists of planktonic species in top samples of three long cores from the Tyrrhenian Sea, but suggests that at least one of these does not represent the modern fauna. MURAOUR (1954 A, B) gives quantitative data for two stations near Algiers. DI NAPOLI-ALLIATA (1952) gives a very useful résumé of the literature on Mediterranean planktonic faunas.

The stations (Fig. 1, Table I) are scattered throughout most of the area south of North Latitude 38° 51′ with the exception of four in the northern part of the Aegean Sea. No samples were obtained from the Adriatic Sea, where many of the previous studies have been made, nor from the northern part of the western Mediterranean. The samples were collected with a gravity corer or with a coring tube attached to a camera and are believed to contain material from the surface of the sediment. Three hundred to five hundred planktonic specimens larger than 0·149 mm were counted from each and the relative abundances of the species calculated. Samples having fewer specimens are omitted; the majority contain many more.

SURFACE TEMPERATURE AND SALINITY DISTRIBUTION

For convenience in the later discussion of the planktonic populations, the area may be divided into three parts: western Mediterranean, eastern Mediterranean, and the

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* Contribution No. 20, Marine Foraminifera Laboratory; Contribution No. 803, Scripps Institution of Oceanography.

Aegean Sea. The depth of the surface-water layer in the Mediterranean is approximately 200 m or less. Although planktonic Foraminifera have been found living at greater depths it is probable that they are most abundant in the upper layers (Phleger, 1954) and it is assumed here that the characteristics of the surface layer are those to which they are adapted.

The eastern and western basins of the Mediterranean are separated by a sill, between Sicily and Tunis, having a maximum depth of about 400 m. The western basin (Tyrrhenian Sea and Algiers-Provençal Basin) is separated from the Atlantic by a sill depth of 320 m. Water enters the Mediterranean from the Atlantic and passes from the western basin to the eastern basin by surface currents. In both cases water flows westward at intermediate depths. A study of numerous sources of information shows that the surface temperature variation in the western area is approximately 13° C to 24° C, the warmest season being in July-August and the coldest in February-March. Greater extremes are found at various near-shore areas, especially along the coast of France. The temperature of the surface water just east of Gibraltar in August, 1938, was 19·5° C rising to 24° C farther east (Rouch, 1940). Surface salinities vary from 36‰ at Gibraltar to 38‰ near Sicily. Variable salinities are often found at near-shore localities. In 1949-50 at Monaco there was a winter variation from 36·8‰ to 38·5‰ and at Algiers 34·5‰ to 37·6‰ (Kruger, 1950). The eastern basin (Ionian Sea and Levantine Basin) apparently contains surface water derived chiefly from the west via the surface current through the Sicily-Tunis gap. The deep water, according to Pollak (1951), is all derived from the Adriatic Sea. Little is known at present about the influence of the Suez Canal, but it is probable that any water derived from this source would quickly lose its identity. Surface temperatures in this area vary from 16° C to 24° C in the western part and 16° C to 28° C in the extreme east. Surface salinities vary from 38‰ in the west to approximately 39·5‰ in the east but here again local variations may occur near shore. An example of this is the comparatively low salinity of 30‰ found off Gaza, Israel, in September, 1947, due probably to the Nile flood (Oren, 1952). Surface currents enter the Aegean Sea from the southeast and from the Black Sea. Surface temperatures vary from 13° C to 25° C and surface salinities from approximately 30‰ near the Dardanelles to 39‰ just north of Crete. Due to the counter-clockwise surface circulation, salinities on the eastern side are higher than those on the western.

These data show that there are lower winter temperatures and somewhat lower salinities in the western than in the eastern Mediterranean. In the Aegean there are lower winter temperatures than in the eastern area and a complex salinity pattern with comparatively low salinities in the northern part.

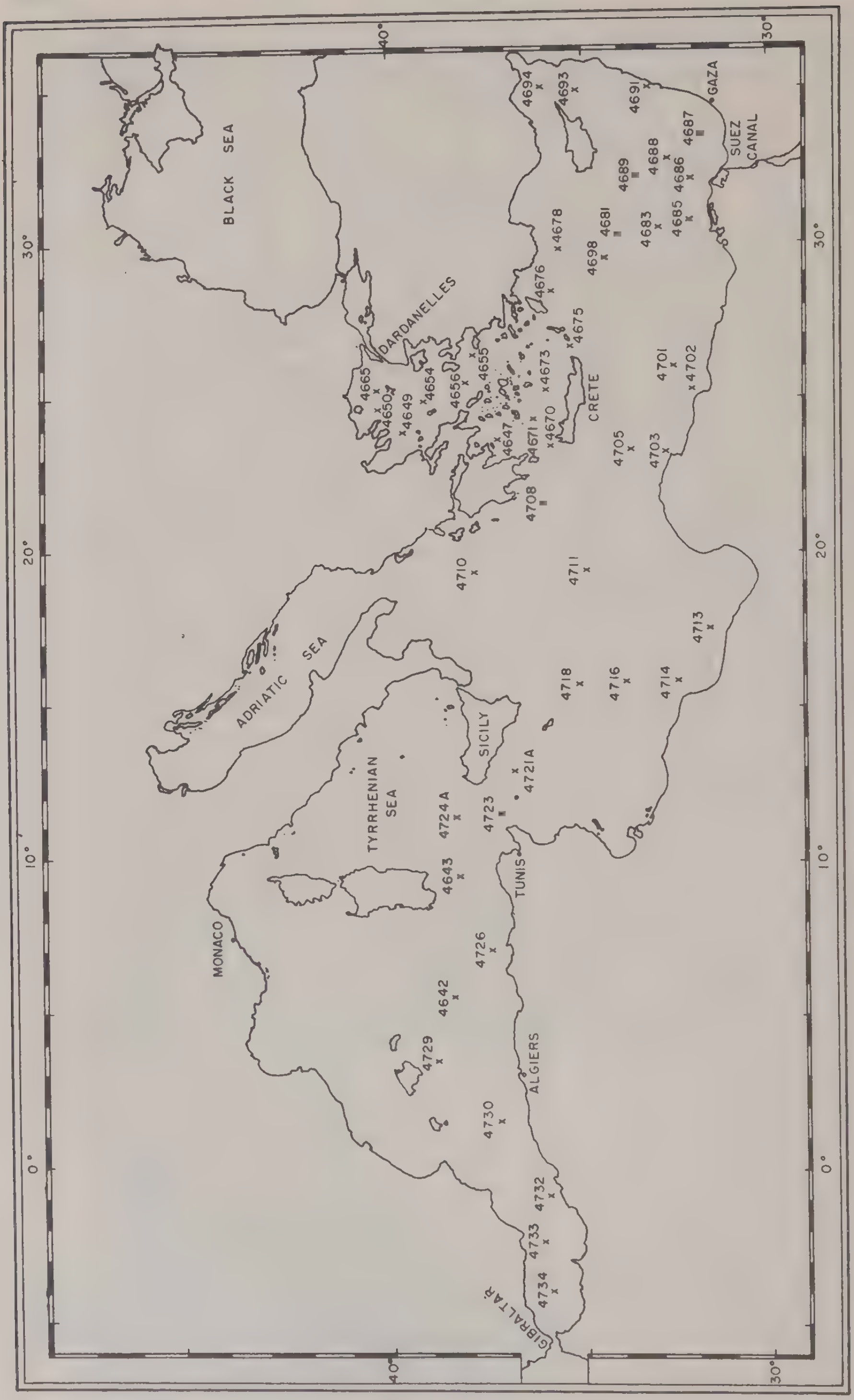
Conditions in the Atlantic immediately west of Gibraltar are also of interest. Here the surface temperature variation is somewhat less than in the Mediterranean, 16° C to 22° C. The surface salinity is somewhat less than that obtaining at Gibraltar.

DISCUSSION OF PLANKTONIC POPULATIONS

The identifications of the planktonic species are in most cases the same as those given by Phleger, Parker and Peirson (1954) in their study of Atlantic deep-sea cores. Some species groups, as defined here, contain forms recognized as species or varieties by some authors. Their omission does not necessarily indicate that they are believed to be invalid. *Globigerinoides rubra* probably includes, or in some cases is

Table I. *Percentage distribution of planktonic Foraminifera in the Mediterranean Sea and adjacent Atlantic Ocean.*

	ATL.			MEDITERRANEAN																																												
STATION	4637	4736	4735	4734	4733	4732	4730	4729	4642	4726	4643	4724A	4723	4721A	4718	4716	4714	4713	4711	4710	4708	4705	4703	4702	4701	4676	4678	4698	4681	4683	4685	4686	4689	4688	4687	4691	4693	4694	4670	4671	4673	4675	4647	4656	4655	4654	4649	4650	4665
DEPTH IN METERS	4182	4420	1292	1340	1919	2471	2766	2481	2870	2775	1609	380	567	179	541	1378	665	684	3309	3241	3499	1788	552	799	2760	3974	1862	2738	2852	2358	647	799	2442	1312	631	1331	1073	567	996	1016	1844	1064	366	680	1102	746	1265	859	1587
N. LATITUDE	35°22'	34°10'	35°17'	36°01'	36°08'	35°59'	37°15'	38°51'	38°26'	37°26'	38°17'	38°22'	37°12'	36°49'	35°06'	33°52'	32°30'	31°37'	34°58'	37°49'	36°01'	33°44'	32°48'	32°05'	32°33'	35°46'	35°34'	34°24'	34°03'	32°59'	32°06'	32°06'	33°32'	32°42'	31°49'	33°17'	35°08'	36°02'	35°49'	36°16'	35°55'	35°21'	37°09'	37°59'	37°50'	39°04'	39°35'	40°14'	40°15'
LONGITUDE	10°23'W	10°30'↑	07°25'	03°58'	02°21'	00°53'	01°30'E	03°27'↑	05°33'	07°02'	09°31'	11°22'	11°34'	12°54'	15°44'	15°47'	15°49'	17°32'	19°24'	19°19'	21°37'	23°18'	23°13'	25°16'	26°03'	28°28'	29°49'	29°34'	30°12'	30°28'	30°41'	32°05'	32°09'	32°43'	33°29'	34°59'	34°56'	35°03'	23°27'	24°18'	25°16'	26°40'	23°38'	25°31'	26°25'	24°54'	23°53'	24°42'	25°18'
Globigerina bulloides d'Orbigny	38	27	40	51	56	52	29	22	25	31	40	35	23	20	9	11	13	17	17	15	16	10	11	14	16	18	18	10	15	7	14	13	16	11	9	8	14	16	11	17	11	18	18	16	22	22	16	15	18
G. digitata H. B. Brady			.3	.4	.2	.4	.7	1	.2				.3			.8	1	.6	1	2	2	.5	.2			.2	.2		1	.7		.3	.2	.6	.3	.2	.8			.3	.3	.2				.4	.3	.2	
G. eggeri Rhumbler	2	1	3	1	2	.7	.8	3	1	2	5	18	5	2	10	2	2	2	9	10	6	4	3	3	3	6	13	10	6	3	3	5	6	6	6	34	13	19	20	28	22	25	16	22	27	25	3	4	21
G. inflata d'Orbigny	10	8	11	29	28	33	38	28	26	21	14	14	35	31	5	6	3	.4	5				.2		4			1				.3	.2							11		6	2						1
G. pachyderma (Ehrenberg)		.8	.2	.4	.6	.3		.6	.2	.3	1	4	.3		.4	.3	.2	.4	3	.2	.5		.2		1	.2	1	2		.1		.8	.5	.3	.3	4	1	2	2	4	.5	4	.7	2	.8	1	.7	2	2
G. quinqueloba Natland				.4		.1					.2	8	1	1	.6	.8			2					.2		1	.4	1			.2	.3		.3		2			.6	1	.5	1	.7			.8	5	2	4
Globigerinella aequilateralis (H. B. Brady)	1	2	3	1	1	.1	1	2	3	2	2	.2	1	1	5	4	1	2	3	1	4	3	2	.5	7	1	1	2	.6	2	1	.5	.2	1	.5			.3	2	.8	1	1	.4	2	.8	.8	.7	1	1
Globigerinita glutinata (Egger)		4	4	1	.4	.7	2	.2	.7	3	3	2	1	1	.4	1	2	.2	4	1	3	.5	.2	.7	4	.7	1	2	.2			.5	.7		.7	.2	.4	.3	.7	2	1	1		.5	.6	2	4	1	
Globigerinoides conglobata (H. B. Brady)	5	1	.2																.1																														
G. rubra (d'Orbigny)	23	24	16	10	9	8	17	25	24	20	23	14	23	35	51	54	55	64	41	64	52	70	70	72	48	68	59	61	60	71	77	69	63	67	68	44	65	59	60	33	59	36	59	52	47	47	69	73	51
G. sacculifera (H. B. Brady)	10	9	9	3	.7	1	.6	2	2	5	.4	.6	2	3	13	11	10	10	4	3	12	10	12	7	14		5	7	11	12		5	10	11	8		3	.1	1		1	.2	3	3		.4	.3		
Globorotalia hirsuta (d'Orbigny) & var.	2	6	3	.4		.1																																											
G. punctulata (d'Orbigny)			.5																																														
G. scitula (H. B. Brady)	2	2	2	.3			.1				.2	1				.5			4							.2		.7								8				2		1						.2	
G. truncatulinoides (d'Orbigny)	6	11	5	.4	.6	2	8	11	14	12	8	1	5	4	2	1	1	.2	1	.2								.2												.3		.2	.2						.3
Hastigerina pelagica (d'Orbigny)									.2							.5	.7	.4		.6	.7			.7	1	.7	.4		.3	.3	.2	.3	.5		.5		.8	.3	.6		1								.3
Orbulina universa d'Orbigny	.3	2	3	1	2	1	3	5	4	4	3	2	3	2	3	7	12	2	4	3	5	2	1	2	2	3	1	3	7	4	5	6	2	3	7		1	3	2	1	3	5	.2	2	2	.4	1	1	1
Pulleniatina obliquiloculata (Parker & Jones)	.3	1																																															


BLACK SEA
DARDANELLES
ADRIATIC SEA
TYRRHENIAN SEA
SICILY
CRETE
MONACO
TUNIS
ALGIERS
GIBRALTAR
GAZA
SUEZ CANAL
40°
30°
20°
10°
0°
4694
4693
4691
4687
4688
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4683
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4734

Fig. 1. Mediterranean Sea showing locations of stations.

synonymous with, *G. elongata* (d'Orbigny) and *G. helicina* (d'Orbigny), reported by D'ORBIGNY from Rimini, Italy, *G. adriatica* (Fornasini), and *G. rubra* var. *pyramidalis* (vanden Broeck). *G. sacculifera* includes a form listed by various authors as *G. triloba* (Reuss) and described by REUSS from the Miocene of the Vienna Basin. Specimens of *Globigerina eggeri* are small but otherwise typical except for Aegean specimens which frequently have a final whorl consisting of 3½ chambers. The latter are similar to *G. bulloides* and further study may modify the ratios of the two species in Aegean Sea samples. *Hastigerina pelagica*, not reported from the Atlantic in significant numbers, is found in low frequencies chiefly in the eastern Mediterranean.

The relative percentages of the planktonic species are listed in Table I. Included in this table, for comparative purposes, are data for three stations from the Atlantic in the general vicinity of Gibraltar. The data for stations 4637 and 4736 are taken from PHLEGER, PARKER and PEIRSON (1954). The following discussion deals only with occurrences as they appear in this table. Species with frequencies of less than 0·2%, therefore, are not included although they may occur. The sampling is sparse for such a large area but the percentage data show clearly that there are three distinctive populations. The first of these is that of the western Mediterranean which extends east to include station 4721A. This assemblage differs from that of the adjacent mid-latitude Atlantic in the following ways:

	Atlantic (mid-latitude)	*Western Mediterranean*
Globigerina digitata	absent	present
G. inflata	8–13%	14–30% (usually more than 20%)
G. quinqueloba	absent	present
Globigerinoides conglobata	present	absent
G. sacculifera	9–10%	less than 1–5%
Globorotalia hirsuta	present	first 2 stas. east of Gibraltar only
G. punctulata	present	absent
G. scitula	2%	less than 1% (scattered)
Hastigerina pelagica	absent	present (1 sta.)
Pulleniatina obliquiloculata	present	absent

The second assemblage is found in the eastern Mediterranean. It differs from that of the western area in the following ways:

	Western Mediterranean	*Eastern Mediterranean*
Globigerina bulloides	20–56%	8–18%
G. inflata	14–38%	0–6%
Globigerinoides rubra	1–25%	41–77%
G. sacculifera	1–5%	3–14% (except 4 stas.)
Globorotalia truncatulinoides	less than 1–14%	0–2% (scattered)
Hastigerina pelagica	at 1 sta.	consistent occurrence

The third assemblage is found in the Aegean Sea. It differs from that of the eastern Mediterranean in the following ways:

	Eastern Mediterranean	*Aegean Sea*
Globigerina eggeri	2–13% (except 2 stas. off Israel)	3–28% (mostly more than 20%)
G. pachyderma		slight consistent increase
Globigerinoides sacculifera	3–14%	0–3%

In the western Mediterranean the population must be adapted to a wider temperature range than that found in the adjacent Atlantic. The winter temperatures are more nearly analogous to those found on the western Atlantic continental slope in mid-latitudes. In some respects the western Mediterranean population reflects this and shows a resemblance to the populations in that area (PARKER, 1948; PHLEGER, 1939, 1942) as shown by the high frequencies of *Globigerina bulloides* and *G. inflata* and the low frequency of *Globigerinoides sacculifera* as well as in lesser respects. The fauna occurring at the three stations (4732–4734) just east of Gibraltar is of interest. Two of these stations lie within the low temperature area reported by ROUCH (1940). Here exceptionally high frequencies of *Globigerina bulloides* and low frequencies of *Globigerinoides rubra* and *Globorotalia truncatulinoides* are found. Whether or not these changes are due to a lowered mean temperature maximum is a matter of speculation. The presence of *G. hirsuta* in significant frequencies in this area may be due to transport by the entering Atlantic current. The faunas reported by MURAOUR (1954 A, B) from the vicinity of Algiers show a much lower percentage of *Globigerinoides rubra*. The populations reported by PHLEGER (1947) from the Tyrrhenian Sea are analogous to those found in the present study.

The increase in the mean minimum temperature in the eastern area from 13° C to 16° C may account for some or all of the shifts in population found there, as similar trends occur when passing from mid to low latitudes in the Atlantic. In general there is a decrease in such species as *Globigerina bulloides* and *G. inflata*, which occur in high frequencies in mid-latitudes, and an increase in *Globigerinoides sacculifera* which is found in increasingly high frequencies in low latitudes.

In the Aegean Sea the mean minimum temperature is 13° C, as it is in the western Mediterranean, which may account for the more consistent occurrence of *Globigerina pachyderma* and the decrease in *Globigerinoides sacculifera* as compared to eastern area occurrences. Lower salinities in the northern part and/or changes in the chemistry of the surface water resulting from the inflow of water from the Black Sea may also account for these changes. This may be especially true in the case of the high frequencies of *Globigerina eggeri* and the fact that many of the specimens are atypical.

The populations at several stations, besides those noted previously, show unusual features but two are especially noteworthy. Station 4724A contains what appears to be a "colder water" fauna. There are higher frequencies of *Globigerina eggeri*, *G. pachyderma*, and *G. quinqueloba* and lower frequencies of *Globigerinella aequilateralis* and *Globigerinoides rubra*. *Globigerina eggeri* is the only species of the group which does not fit this pattern, since that species is found in higher frequencies in low latitudes. Further study may reveal whether or not this fauna is pre-modern. The sample from station 4718 contains a large percentage of weathered, discoloured specimens, some of which are filled with glauconite. This suggests that little deposition has taken place in this area for a long time, since at most stations the planktonic specimens appear to be fresh and well-preserved, showing recent deposition. It is possible that there is a strong current in this area which removes the specimens as they are deposited, leaving the older, filled tests.

The planktonic populations in the Mediterranean probably are derived in two ways: from material brought in by the Atlantic current and from ancestral stock indigenous to the area, a so-called " relict " fauna. A third possible source may be transport through the Suez Canal, but too little is known about this at the present time to evaluate its importance. A study of Table I and of the specimens themselves leads to some interesting speculations on this point. PHLEGER (1947) believes that occasional specimens of *Globorotalia scitula* are introduced from the Atlantic, but that the species is not found living here. The present findings point to the same source, but it is probable that there is some survival as there is a scattered occurrence of the species throughout the area. *Globigerinoides conglobata* and *Globorotalia hirsuta*, which occur rarely at many stations, may have a similar origin. On the other hand *Globigerina digitata* and *Hastigerina pelagica*, which are rare in modern Atlantic sediments, may be species indigenous to the Mediterranean. The atypical form of *Globigerina eggeri* found in the Aegean Sea is probably an indigenous form.

A recent study of the coiling direction of *Globorotalia truncatulinoides* by ERICSON, WOLLIN and WOLLIN (1954), shows that the North Atlantic may be divided into provinces in which there occur " races " showing a dominance of left or right coiling. According to their interpretation the area immediately west of Gibraltar should contain a population showing equi-directional coiling. Samples from *Atlantis* stations 4637, 4735 and 4736 were examined and this was found to be the case. East of Gibraltar at station 4734 the ratio shifts to 79% left coiling (based on 62 specimens) and increases rapidly to the east until at station 4730, just east of 0° Long., a dominance of 99% left coiling is found. High ratios of 88% or more are maintained eastward to station 4711, just west of 20° E. Long., which shows 62% left coiling. Farther east there are too few individuals to give significant results. Where possible, 400 specimens were counted and such samples served to check neighbouring stations containing fewer specimens. These results also suggest that at least part of the Mediterranean populations are indigenous and not directly derived from the Atlantic. A study of other species by statistical analysis of measurements or other characteristics and a comparison with Atlantic specimens would give additional data on this point.

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Printed in England by Page Bros. (Norwich) Ltd.

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Papers in Marine Biology and Oceanography, pp. 45-57. Pergamon Press Ltd., London.

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Foraminiferal faunas in cores offshore from the Mississippi Delta*

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Summary—Study of Foraminifera from fifteen cores shows presence of cold-water faunas interpreted as representing glacial stages and/or substages, and of warm-water faunas interpreted as post-glacial and interglacial stages and/or substages. These sequences are similar to those previously reported from the northwestern Gulf of Mexico.

The amount of post-glacial deposition is greater on the lower continental shelf and upper continental slope than on the lower slope and basin. Variations in amount of post-glacial sedimentation within these topographic provinces are demonstrated.

Two cores located in the bottom of Mississippi Canyon contain faunas and sediments which have been displaced downslope, presumably by turbidity currents. It is suggested that the turbidity current was confined to Mississippi Canyon, and that submarine canyons generally tend to localize many turbidity currents.

INTRODUCTION

Members of the Woods Hole Oceanographic Institution have pioneered in studies of the offshore sediments in the northern Gulf of Mexico. Extensive collections of surface sediments and longer cores were taken along 2,500 miles of traverses in the northwestern Gulf of Mexico in 1947, using the research vessel *Atlantis*. The physical parameters of these sediments were reported and interpreted by Stetson (1953), chemical studies of the materials are discussed by Trask (1953), and the foraminiferal faunas are described and interpreted by Phleger (1951) and Phleger and Parker (1951). In 1951 Stetson made extensive collections aboard the *Atlantis* in the northeastern area, from the Mississippi Delta to Florida, collecting surface sediment samples and long cores along several hundred miles of traverses. The foraminiferal facies in the surface sediments along these traverses have been interpreted by Parker (1954), and study of the sediments is being undertaken by Stetson.

The present paper is a study of the vertical sequences of foraminiferal faunas in fifteen of these cores in a traverse extending southward from the Mississippi Delta. The purposes of this study are:

(1) To discover whether there is a vertical sequence of cold- and warm-water faunas as reported from the western Gulf of Mexico and elsewhere;
(2) To attempt to discover relative rates of deposition off a large delta;
(3) To evaluate the role of turbidity currents in deposition in the area covered by the cores.

The cores were studied at the suggestion of Henry C. Stetson of the Woods Hole Oceanographic Institution, who furnished them to the writer. The assistance of Jean F. Peirson in this study is gratefully acknowledged. Dr. Rufus J. LeBlanc, of the Shell Development Company, kindly arranged to have several of the cores sampled. The laboratory work was supported by the Office of Naval Research (Project NR 081–050, Contract Nonr–233, Task 1).

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* Contribution No. 21, Marine Foraminifera Laboratory; Contribution from the Scripps Institution of Oceanography, New Series, No. 804.

LOCATIONS OF STATIONS AND DESCRIPTION OF THE AREA

The cores were collected along a traverse (Table I, Fig. 1) extending from the deep Gulf of Mexico basin at 3,017 m to the lower continental shelf at 88 m. The near-shore, shallow end of the traverse is only a short distance off Southwest Pass, one of the main distributaries of the Mississippi Delta.

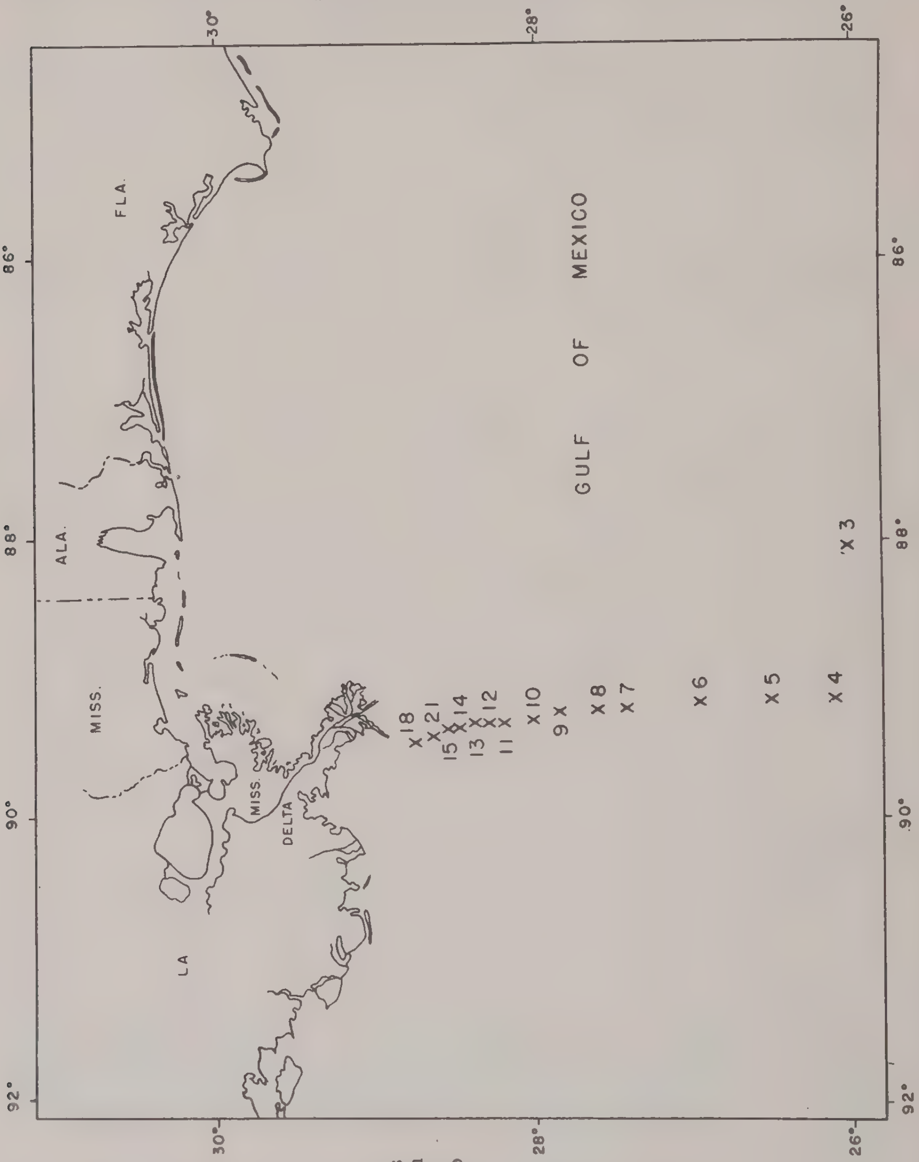

30°
28°
26°
86°
88°
90°
92°
FLA.
ALA.
MISS.
LA
MISS.
DELTA
GULF OF MEXICO
X 3
X 4
X 5
X 6
X 7
X 8
9 X
X 10
11 X
X 12
13 X
X 14
15 X
X 21
X 18

Fig. 1. Locations of cores in the Gulf of Mexico off the Missis-sippi River.

Table I—Locations and depths of cores

Core	*Depth in m*	*N. Lat.*	*W. Long.*
3	3017	26° 01′	88° 03′
4	2972	26° 07′	89° 09′
5	2788	26° 31′	89° 09·5′
6	2468	26° 58·5′	89° 12′
7	1875	27° 26′	89° 14′
8	1417	27° 37·5′	89° 14·5′
9	1372	27° 51′	89° 15′
10	1298	28° 01·5′	89° 19′
11	914	28° 12′	89° 20′
12	732	28° 18′	89° 20′
13	631	28° 23·5′	89° 20′
14	471	28° 29′	89° 22′
15	298	28° 33·5′	89° 22′
21	142	28° 39′	89° 25′
18	88	28° 45·5′	89° 27′

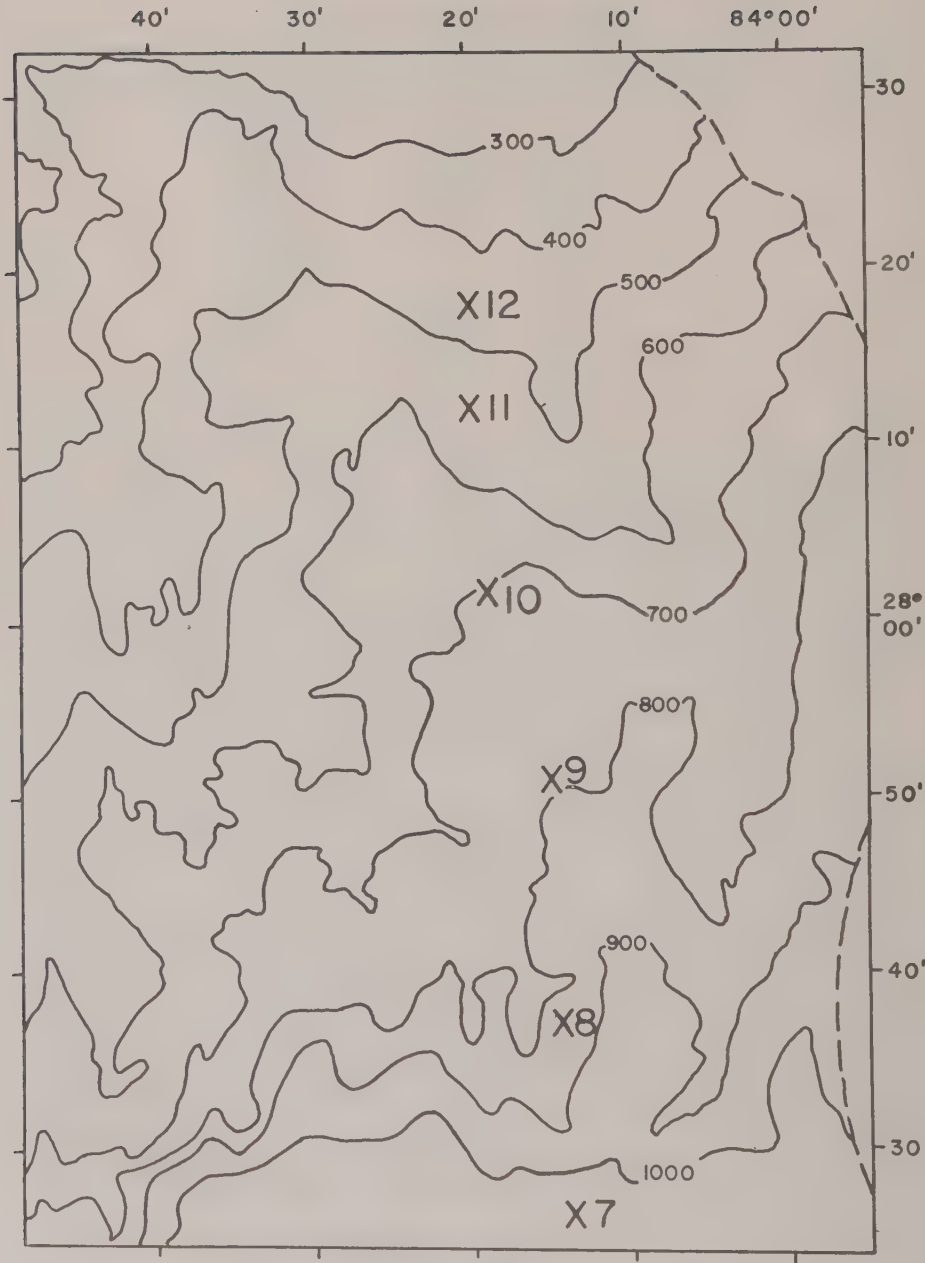
The topographic charts of the northwestern Gulf of Mexico, constructed by Gealy (1955), end at the approximate position of the Mississippi Delta, and all of the present core stations are off her chart except cores 7–12 (Fig. 2). Core 18 was taken at a depth of 88 m on the lower part of the narrow continental shelf. Most of the other cores came from the continental slope, except those at the outer end of the traverse which are in or on the edge of the Gulf of Mexico basin. The continental slope in this area appears to be quite rugged, and is cut by the Mississippi Canyon. The Sigsbee Deep Scarp described by Gealy may not be present in the area traversed by the cores.

This is an area of high runoff from the Mississippi River and is presumed to have a rather high rate of sedimentation. It has been shown by SCRUTON (MS.) that the highest sedimentation rate is close to the delta distributaries and decreases rapidly offshore. There appears to be rather rapid sedimentation for approximately 60 miles offshore, according to analyses by PHLEGER (MS.). It seems likely that sedimentation is more rapid farther offshore in this area than in any other part of the northern Gulf of Mexico.

The physical oceanography of the area is not well-known. Offshore surface temperatures vary from a mean minimum of 20° C in February to a mean maximum of 29° C in August, according to FUGLISTER (1947). It thus has the surface-water temperatures of North Atlantic mid-latitudes in winter and of low latitudes in summer. A considerable amount of low-latitude water enters the Strait of Yucatan, and while much or most of this flows out the Florida Strait, its effect may be pronounced in the area of the outer part of the present traverse. Offshore salinities in the Gulf of Mexico are approximately 36°/₀₀. A near-shore wedge of lower-salinity water is expected in this high runoff area. PARR (1935) shows salinities of approximately 24°/₀₀ in the upper 50 m a few miles to the east of the present traverse.

METHOD OF STUDY

The cores were collected with a coring tube described by HVORSLEV and STETSON (1946). The samples used in the present study were one-fourth of each core cut into sections approximately 5 cm in length, so that the entire core was sampled. Each sample was trimmed of approximately 1/8 inch of sediment to prevent contamination between samples and was washed free of fine sediment over a brass sieve having an average opening of 0·074 mm.


40'
30'
20'
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84°00'
30
20'
10'
28°
00'
50'
40'
30'
300
400
500
600
700
800
900
1000
X12
X11
X10
X9
X8
X7

Fig. 2. Locations of cores 7–12 in relation to topography. Topography modified after Gealy (1955). Depths in fathoms

The foraminiferal faunas were analyzed quantitatively. Only a fraction of the population was counted in samples having very large populations; quartering was done by a method described previously (PHLEGER, 1951, 7). Occurrences of species are listed in percent of the total; benthonic and

Table II—Occurrences of Foraminifera in cores 3–6, in percent of total population. Planktonic and benthonic populations computed separately

CORE	6																			5							4															3										
DEPTH IN METERS	2468																			2788							2972															3017										
DEPTH IN CORE IN CM. FROM TOP	TOP	4-8.5	12.5-17.5	20-25.5	27.7-32.5	32.5-37.5	42-47	54-59	75-80	90-95	98.5-104	110-115	131-136	148-153	170-175	178-183	190-195	202.5-207.5	207.5-213.5	TOP	8.5-14.5	44-49	71-76	109-114	134-139	167-172	TOP	0-5	11.5-15.5	23.5-28.5	31.5-36.5	47.5-52.5	57.5-62.5	82-87	110-115	120-125	148-153	160-165	165-170	170-175	181.5-186.5	TOP	5-10.5	10.5-15.5	31.5-38.5	38.5-43.5	57-62	76-81.5	85-90	102.5-107.5	130.5-135.5	167-172
TOTAL PLANKTONIC POPULATION	52,000	98,000					140,000		1,700		16,000	2,800	510		90		12			14,000	70,000	45,000	1,300	2,700	51,000	2,700	27,000	8,900		48,000		5,000	3,600	990	250						37	63,000	56,000		68,000		32,000	3,000	1,400	2,100	960	
Globigerina bulloides	4	.8					1		.2		10	4	2		8		8			5	2	5	1	.9	4	.9	8					.8	1	2	.4							3	2		2		5	7	10	5	9	R
G. digitata																				.2							1															.1										
G. eggeri	7	12					12		14		9	9	14		2		8			5	7	9	12	11	11	11	10	7		12		11	7	4	20		X	X	X	X	8	6	7		8		10	11	11	9	10	
G. inflata																												.3																			.2		.3		.9	
G. pachyderma													.4																			.6	.3	.4	.4												.4	4	1		4	
Globigerinella aequilateralis	5	4					4		1		2	.6	.4		1					5	2	4	3	2	4	4	5	3		1		.8	3	4	2						3	4	6		5		2	6	6	3	1	
Globigerinita glutinata	3	1					3		2		6	3	8		6					12	17	15	11	8	24	17	9	10		10		10	8	3	6							13	5		4		12	8	7	13	8	A
Globigerinoides conglobata	.5	.3					.5		.7		.6	.8								.1	.4	.3	.3	.3			1	.3		.7			2	.4	.8							.2	.9		.4			.9	1	.7	2	
G. rubra	45	23					23		29		51	43	55		49		43			46	36	27	34	37	32	44	36	37		41		55	56	38	41		X	X	X	X	62	42	42		40		38	44	36	41	43	A
G. sacculifera	17	31					40		31		5	27	4		26		25			7	9	16	22	20	9	7	9	16		18			8	38	10		X	X	X	X	8	9	15		26		16	7	9	17	6	A
Globorotalia hirsuta																																											.2				.2	.2	1	.4	.3	
G. menardii	5	8					3		5		.3	3					8			3	8	8	4	5	3		4	4		4					.8		X	X				4	6		4		1			1		C-R
G. punctulata	1	4					1		1		7	3	3		2		8			.5	.7	1			2	5	.2	.6				2	7	.8	7		X	X	X	X	8	.1	.3		.2		3	3	8	.7	4	
G. scitula	1										.9		1							7		.3			.6	1	4			.2			.3									3	.6		.2		1		2		.3	
G. truncatulinoides	3	4					1		3			3	8		2					2	4	3	2	2	2	2	2	7		2		.6	1	2	8		X	X			8	2	2		.8		2	1		1	7	R
G. tumida	1	3					1		2			.3	.4		1					.2	4	3	2	1	2	2	2	6		2		3									3	.3	2		3		3	.2		.6		R
Orbulina universa	3	3					7		6		2	.6	3							1	7	3	3	9	3	3	5	4		5		4	4	.8	3		X	X				1	6		3		4	6	3	4	4	
Pulleniatina obliquiloculata	3	5					3		4		6	2	.8		3					2	2	4	4	3	3	4	3	5		4		2	2	6	.4			X				1	2		3		2	1	5	3	.9	
Sphaeroidinella dehiscens	.1	.5					.3		.2			.3										.7	.6	.3			.2					.6	.3																			
TOTAL BENTHONIC POPULATION	550	1,000	1,700	1,700	2,500	1,800	1,100	56		17	530		76	210		14		7	5	700	1,100	1,000	240	100	1,500	360	510		570	1,000	600	400	140	150		220	40				23	1,200		1,600	600	310	650	210		170	170	22
Amphistegina (juvenile)																																												.5		.6				.6		
Angulogerina bella																																													.7							
Bolivina alata					.6	.9															.7	.8		1	4	.3	.8				.3											.3			.7							
B. albatrossi				.5		.4		2																		.3					.3																					
B. lowmani		.8		.5	1	2	2				.2									2	3	5	6	2	2	.8	.4		1	1	1	.2										4		2	12	3	1	.5		1		
B. paula		.8					2															2		1	1		.4		1	.8	.3											1		1	.7	1	.6					
B. pulchella primitiva	.4				.6															.6					.5		.4			.4												2		.5		1						
B. striatula spinata								2														.4	.4																													
B. subaenariensis mexicana	.4					.4							1								.4	.8			.5					.4	1													.5	.7	1						
B. subspinescens	.4				.3		.8				1									1	1	1		1	2	.3	1			.8												1		.5	.7							
Bulimina spicata			.2	.5				4		6																																										
B. striata mexicana	1	.8	1	.9	.6						.2									.6						.3										.5						.3										
Buliminella cf. bassendorfensis				.5																		.4	.4	1	.3	.5					.3	.5										.7					.3					
Concris oblonga																																													.7							
Cassidulina subglobosa	6	5	4	5	2		2						1	.5						4	4	.4	.8	2	2	2	3		2	3	.7	.5	.7	.7		.5	2				9	2		2	5	5	2	1		.6	.6	10
Cassidulinoides tenuis	.4				1	.4							3			7					.4	.8				.5										1	20				53	.3		.5			.3					
Cibicides kullenbergi		1	1	1	3	2	2				2											1			.3		.4		.7	.8		.2													1							
C. robertsonianus	4	8	7	3	3	4	2	2		6	7			.5						3	4	3	.4	1	3	.5	6		3	2	1	1	.7	1								.7			.7	.6	.9	.5		.6		
C. wuellerstorfi	18	12	18	13	10	12	13	11		6	2		4	13		7		14	20	3	5	12	2	8	10	7	20		24	18	24	21	21	5		10	20				4	13		20	16	23	21	21		5	24	35
Eggerella bradyi	1	.4	1	.5	2	1	2			6	2										2	.4		1		.3	1		.7	.8	.3	2	3			.5						.3		.5	1	1	.3	1		2	.6	
Elphidium spp																					.7								.3	.4																.6	.6			1		
Epistominella decorata	4	4	2	2	1	4	3	4		11	19		1	.5						20	9	8	2		14	11	8		8	4	10	2	6	.7		.5	2					21		20	9	4	14	3		5	2	5
E. exigua	.4	.4	.2								.8									2	1	.8			.3	1			.3													1					1					
Eponides polius	3	1	2	.5		4					1			.5						8	6	2	.4		.8		4		9	6	4	.2										6		4	1	.6		1		.6		
E. tumidulus	.4	.8	1							19	.9		1	3						3	5	2	.8		2	.8	6		5	9	3	3	1	4		2						3		2	13	7	9	2		.6	5	9
E. turgidus	4	2	3	1	2	9	2	4			13		7	27						12	8	7	9	18	9	14	4		9	9	18	38	36	26		7	7				4	6		7	5	4	13	31		38	18	9
Globobulimina affinis & vars	5	12	8	11	14	15	15	9		6	18		48	44		7				1	4	4	50	5	9	36			10	3	.7	2	5	50		55	36				9			2		.6	4	11		5	28	5
Gyroidina neosoldanii			2	9	6	9					1										.4	.4			.3				.3	.4		.2	1	.7		.5								.5		3	.9	1		1		
G. orbicularis	3		.5	.5	1	1					1			.5						1	2					.3				.8	1	.5																				
Haplophragmoides bradyi	3		2																		2						2															2		.5	.7							
Hoglundina elegans	4	14	14	30	28	25	14	28		11	10			1						.6	4	13	6	31	4	6	2		4	6	10	2		1								3		8	5	9	5	3		2		
Karreriella bradyi																																																				
Lagenidae	6	8	5	6	7	7	4	4		6	2		5	1						10	11	12	9	15	12	4	2		7	7	6	2	4	2		3						5		7	7	11	4	5		4	5	
Miliolidae	.4	2	.2	2	6	2	8													1		.4	2		.5	1	.8		1	1	.3											.6				1	1	2			1	
Nonion pompilioides	2	1	2	3	3	2	2	2			.2		3	.5						.6	2	5	.8	3	2	3	2		3	4	4	2	1	3		.5						1		2	7	7	6	1		2	4	
Nonionella atlantica																						.4																				.7					.3					
N. opima							2																																													
Plectina apicularis	.7		2																								3			1												1										
Pseudoeponides umbonatus	3	3	3	3	3	3	3	2		11	1		8	2		50				1	2	.4	.4		2	3	.4		2	.8	2	5	9			3						1		2	.7	6	2	7		2		
Pullenia spp	9	3	5	2	2	5	7	8			3			1						4	7	2	1	1	3	2	2		2	5	3	2	3	.7		.5						.6		4	3	4	2	2		5	3	
Pyrgo murrhina		.4	5	.9	.6	9	.8				3		3	1												1			.3	2		5	.7	2								.3		1		2	.9	2		6	.6	
Quinqueloculina sp		.8		5	1	9	.8	2			.9									.6		.8			1	.5					.3		3													.6	.9	.5				
Robulus spp			.2			.4	.8				.2		1																	.4																					.6	
"Rotalia" beccarii vars			.2			.4																																														5
"R" translucens			.2				2							.5											.3		.8															.3		1				.5				
Sigmoilina distorta																																																	.6			
S. schlumbergeri	.4	2	1	2	.3	1		2			2			.5				29			.7		.8		.3	.3			.7	2	2	1	.7								4	1		1	.7	.6	.3			1		
Siphonina bradyana																							.4																													
S. pulchra																																										.3										
Siphotextularia rolshauseni																						.4	.4		1	.5	1					.5	.7									1		.5				.5				
Triloculina tricarinata					.6		2													1		4	1		2		.4															.7		.5	.7	6	.6					
Uvigerina peregrina	4	8	3	2	3	2	9			6	1		1	.5					20		1				.3		1					.2																				
Valvulineria mexicana	2	1	.7		2	2		4			3		8	2		29		57	40	2	1	2	.4		4	1	.4			.8	2	.5				13	13				4	.7				.6				8	4	22
Virgulina advena		.4		.9																.6	2				.5		.4		.7		.7	.2	1											.5				.5		1		
V. complanata	.4				.3						.6		4						20	.6	2	.8	.8	3	1	1	.4		.3		.3	2	.7	1		1					13	1		.5		1	.6	.5		1	2	
V. mexicana																				.6																						.7		1		.3						
V. pontoni								2														.4																														
Laticarinina pauperata	3	1	2	.5	3	1	.8	2			.6									.6	.4	.4								.4		.5										.3		.5		.3				1		
Other species	11	5	8	5	2	2	5	6		6	3		1							15	10	7	4	6	5	2	26		4	8	3		2	2		1						16		7	6	5	7	3		5	2	

Table III—Occurrences of Foraminifera in cores 7–11, in percent of total population. Planktonic and benthonic populations computed separately

CORE	11								10						9									8										7							
DEPTH IN METERS	914								1298						1372									1417										1875							
DEPTH IN CORE IN CM. FROM TOP	TOP	5-105	62-675	133-1385	170-1755	190-195	203-209	2215-227	TOP	25-7	235-285	565-615	105-110	144-155	TOP	3-8	·95-145	145-195	36-41	545-595	735-785	119-124	158-163	TOP	9-14	35-40	55-60	84-89	89-94	1035-1085	1115-1155	1155-1195	1385-144	TOP	0-5	115-17	155-255	30-35	52-57	95-100	120-125
TOTAL PLANKTONIC POPULATION		3,700	2,700	12,000	9,500	5,200	2,100		1,700	2,300	4,000	900	600		5,300	3,100			6,700		3,200	97	3	7,000	170	180	120	120			2,600			100,000	57,000			28,000	3,400	65	9,200
Globigerina bulloides			4	4	8	4	6		6	2	.4	.9	2		9	1			.5		2	1	13	6		2		.8			2			3	1			4	3	3	5
G eggeri		14	8	19	16	19	11		14	13	14	8	16		10	12			14		11	4	6	18	10	10	8	14			20			8	10			11	9	15	9
G. pachyderma							1																																		
Globigerinella aequilateralis			1	2	.7				4	.3	.8		1		6				2		.7		3	3	2	3	.8	2			1			7	2			4	5	6	1
Globigerinita glutinata		3	6	7	5	2	7		3	4	4	6	3		5	3			4		5	10	10	1	.6	3		6			2			2	2			6	6	8	8
Globigerinoides conglobata		.4	.3			.5	.6		2	.3	2	.4				3			2		.2			3	.6									.5				.3			.3
G rubra		33	37	35	45	48	41		25	25	27	39	31		32	27			33		35	51	33	23	29	22	43	35			33			32	41			35	38	24	36
G sacculifera		17	12	13	8	8	8		6	10	14	13	19		5	13			12		12	8	10	6	36	35	25	6			14			15	17			11	20	24	17
Globorotalia menardii		11	8	.6	X	X	X		9	13	13	8	8		3	13			9		11	7	6	9	7	9	3	7			.3			11	8			9	4	2	.3
G punctulata		2	5	4	6	11	10		1	2	.4				.6	2					2	1	3	.7							13			.4	1			1	.3		14
G scitula			.3				.6		2						2						.2													.5							.8
G. truncatulinoides		6	8	4	2	4	5		13	11	12	9	7		7	12			9		10	6	3	12	5	5	4	4			3			5	5			7	2	6	3
G tumida		2	1	2	3	.5	4		3	3	3	5	2		2	4			2		1	1		4	.6	1	3				3			2	2			2	.9	5	2
Orbulina universa		.9	.9	3	1	1	2		3	4	.8	3	2		8	2			1		3	7		2	7	5	5	10			3			8	4			5	6	2	2
Pulleniatina obliquiloculata		10	8	5	5	2	4		9	12	9	7	8		10	8			11		7	4	13	12	2	5	7	11			5			4	7			4	5	2	2
Sphaeroidinella dehiscens		.4	.3																								.8	2						.2					.3	3	
TOTAL BENTHONIC POPULATION	160	2,100	1,200	2,800	3,700		3,200	530	320	390	830	280		120	380	460	370	780	860	340	410	30	160	430	82		170	200	170	160	250	400	290	180		200	42		280		
Angulogerina bella																							.6																		
Anomalinoides mexicana			.3	.1	.3		.1				.2	.7			.3		.5	.1	.2									1	.6		.4	.2									
Bolivina alata							.1			4		.4		.9		.7	2	.1		3	17		3	2	50		63	12	17	42	30	33	45				32		46		
B albatrossi	3	12	10	.7	1		1		8	11	10	7		.9	.8	4	8	2	5	5	6	3	1	3	2		1	1	2	7			.3	4		1	2		2		
B barbata														3									4																		
B lowmani		1	2	2	.1		.1		2	2	3	.7		7	1	1	2	2	1	.9	1		2	.2	1					1	.4								.7		
B ordinaria		2	2	7	6		12	5		.5	.7					.2			.2	1					1			.5		.6									.4		
B pulchella primitiva														.9																			.3								
B striatula spinata														5		.4				.3	.5		4									.2									
B subaenariensis mexicana		.2					2	.4						2									4	.2	6		.6	1		.6		.2	.7				2		2		
Bulimina aculeata	4	3	1	6	21		16	8	11	15	18	10			13	21	15	10	21	23	16	14	1	2							1	1	1	7		9					
B alazanensis		6	5	1	2		3		5	4	3	3			1	1	1	2	2	3	2			2					1		2	3				.5					
B marginata														5									2																		
B. spicata		2	2	.9					4	.8	2	3			1	.7	.3	.4	.9	.3	2	3	.6	2				.5						2							
B striata mexicana		.2	.5		2		2	3	.6	2	.4					.7		.8	.5	1				.9	1			4	4		.8	2	.3	.6		1			.7		
Buliminella cf. bassendorfensis										1		2		13		.2				.3	1	7	5										1			.5			.4		
Cassidulina carinata		.6	.3	1	4		20	73						.9		.2	.3		.2		.5	20	20				2	.5		1	1	1	.7				2		1		
C. subglobosa		9	4	10	5		5		2	9	11	13			4	5	4	6	5	6	4	3		4	1		.6	1	.6	2	3	7	1	11		3			.4		
Chilostomella oolina		.2		.1			.1		.9	.3						.4					1	7	1				22	.5		4	1	.5	16						.4		
Cibicides aff. floridanus	.6	2	5	4	3		.8	.2	4	5	5	5			3	3	2	2	3	3	1	3		4							.4										
C robertsonianus			2	.1			.1		2	.5	1	2			.8	1	2	2	3	.6	1			.2				.5	.6		2	3		5		3					
C. wuellerstorfi		.2	.2	.1	.3				.9	1	2	1			.8	5	4	2	2	4	3			2	1			1	3		2	2	.7	3		7					
Cibicidina strattoni														2																											
Elphidium spp														4									1										.3								
Epistominella decorata									.3						3	1	2	3	1	.6				2	4			1	4	2	8	5	3	18		1			10		
E. exigua		4	5	12	11		3	.2	4	2	4	4		2	1	1	3	2	3	2	2	7		.5	2		.6	3	1	6	.8	.2	2	3		.5			1		
E rugosa		2	.8	.9	1		.5					.4					.5	.1		.6	.5																				
E vitrea														27									19																		
Eponides polius		.4	.2	.7						.8	1	1		9	.3		2	.5	1	.3	1									.6	.8	.2									
E tumidulus											.8				.3	.9	.3	2	.2		.2								.6					2		1					
E turgidus		8	5	4	2		5		.6	3	5	3			6	7	8	10	21	12	3			.9				1	2	.6	3	1	.7	.6		3	10		5		
Globobulimina affinis & vars.	.6	.6	2	.4	.9		.5		3	2	.5	1		2		4	.8	.1	1	2	2				23		2	30	35	11	10	8	2	2		15	34		14		
G. mississippiensis																							2																		
Gyroidina orbicularis		3	.8	.6	1		1		2	1	2	4			2	3	4	5	4	2	3			4				2	.6		1	1	.7	5		3					
Haplophragmoides bradyi	7								1	.3					.5	2		2						.9										3		.5					
Hoglundina elegans		.7	.2	.3	.2		.1			.8	.7	.4				3	4	2	1	2	.7										4	2		6		11	5				
Lagenidae		2	2	4	3		.3	1	.3	5	4	9			3	4	4	6	4	3	6	7		.7	2			4	1	4	3	2	3	3		4			3		
Laticarinina pauperata		2	.6	1	1		.3		.9	2	2	2			1	2	2	2	1	2	2			.9							2	3		1		2	2				
Miliolidae		.8	2	.6	.5		.2		2	.9	2	.4		5	1	1	1	1	.4	1	1	3	1	.9					.6	1	2	4	3	1					.4		
Nonionella atlantica																																		.6							
N opima														6							.2		1										.7								
Osangularia cultur	.6	7	13	.7					2	3	2	6			.8	3	1	2	3	2	3			3	1		1	5	4	3	1	2	.3	2		3	2		.7		
Pseudoeponides umbonatus			.5	.1	.3		.1		.3	.5	.2	.4			.5	1	1	.3	.5	.3	.5							3	4	1	.4	.7		.6		1			.4		
Pullenia spp.	.6	2	1	1	1		.2		4	2	3	2			1	3	5	3	4	5	2			.9				2	3	.6	2	1	.3	1		4			.4		
Rectobolivina advena																							.6																		
Robulus spp		.2			.3				.3		.6			2		.2	1	.5	.9		.2		2	.7				1	2	1	.4	.2	.7	.6		.5					
"Rotalia" beccarii vars.														4									4																		
"R" translucens		1	3	3	13		12	.2	.3	5	1	5			.3	.9	2	.6	.2	2	3	3	.6							1				.6							
Uvigerina parvula														3									8																		
U peregrina	1	14	21	22	10		5	.2	6	7	8	5			6	8	8	4	5	4	6			15	2			17	8	5	5	6	3	5		15	.2		6		
Virgulina mexicana					.1		.5	7								.2					3	20	3				2	.5	1		.4	.7	6						.4		
V. pontoni														2									2																		
V. tessellata		.2	.6		.1		.3		3	.5	.4	.7				.2	.3		.2	.3	.2																				
Other species	82	3	8	16	10		9	2	29	8	6	8		2	48	10	9	24	4	10	4		8	47	3		5	7	4	5	12	10	7	12		10	7		5		

Table IV—Occurrences of Foraminifera in cores 12–15, 18 *and* 21, *in percent of total population. Planktonic and benthonic populations computed separately*

CORE	18						21						15								14						13						12							
DEPTH IN METERS	88						142						298								471						631						732							
DEPTH IN CORE IN CM FROM TOP	TOP	4-9	45-50	99-104	124-129	162-168	TOP	15-20	44-49.5	74.5-80.5	120-125	192-198.5	TOP	13-19	42-47	55-60	86-91.5	117-122.5	163.5-170	192-197	TOP	4.5-10	48.5-53.5	90-95	124-129.5	180-185	TOP	7.5-13	45-50	86-91	134-139	174-180	TOP	15-20	67-72	85-90	109-114	153-155	170-175	200-205
TOTAL PLANKTONIC POPULATION	3	6	18	8	–	10	0	97	300	140	280	12,000	300	1,700	2,300	24,000	900	170	23		2	9,200	270	16,000	26,000	19,000	7	150	200	850	1,100	5,000	75	250	500	500	2,200	2,500	3,600	11,500
Globigerina bulloides	67							8	4	6	1	1	3	4	3	4	3	3	13			6	3	6	6	16		.7	2	5	4	7	4	5	7	3	1	6	2	7
G eggeri			22	12				14	15	13	11	10	27	10	12	12	12	12	4			11	15	11	12	11		13	7	7	14	9	20	14	11	9	13	14	17	20
G pachyderma																										2														2
Globigerinella aequilateralis						10		1	2			2	.4	1		1	.4	2				1	3	.6	.6	.8		1	.5	1	.7	2		.4	.4	.4	.7		1	.6
Globigerinita glutinata			11		100			6	3	2	7	6	5	2	3	1	3	1				2	2		8	7		5	3	1	4	6	3	.8	2	3	3	3	.9	2
Globigerinoides conglobata								3		2	.7	.6	.7	2		1	.9					.3	2	2	3	.8		1	.5	2	.4	1		1	.8	.4	.4		.4	
G rubra	33	50	27	40		20		44	28	43	35	42	12	38	42	51	40	54	62		100	44	28	39	37	48		27	30	34	29	38		36	35	30	28	41	38	32
G sacculifera		33	6	12		10		4	10	8	12	6	4	16	13	13	18	16	13			8	5	9	17	3		9	12	11	7	10		6	4	10	11	14	21	9
Globorotalia hirsuta													.4	3	2	3	.7	2												.4										
G menardii		17		12				1	7	3	14	10	13	3	2	4	5	3				6	9	8	6		14	11	12	16	12	9		5	3	11	14	4	5	.3
G punctulata								1	.7				.7		.7	1	.4	.6				.7	.7	.6	.3	5	14	3				.3	3	.4			5		.2	10
G scitula																									.3	2														
G truncatulinoides			22			30		9	8	3	4	7	12	10	11	3	6	3				10	11	7	4	.5	29	15	18	9	9	7	43	9	7	8	8	4	4	4
G tumida									3	2	1	1	6	6	4	1	1	1				3	4	2	1			.7	4	3	7	3	4	3	6		5	5	2	6
Orbulina universa			6	12				3	5	5	3	3	1		.4	.7	2		4			2	7	3	1	3		1	1	.7	4	.6	3	3	5	7	2	3	2	1
Pulleniatina obliquiloculata			6	12		30		6	14	13	11	11	14	5	7	4	8	2	4			6	10	12	3	1	43	12	10	10	13	6	20	14	19	17	9	6	6	6
Sphaeroidinella dehiscens																							.4		.6					.4						.4			.2	.3
TOTAL BENTHONIC POPULATION	250	1,200	2,800	1,400	1,100	950	120	4,600	3,900	5,600	4,200	15,000	800	3,500	2,800		1,300	1,300	1,300	1,100	36	5,200	1,800	6,700	6,400	10,000	250	750	800	1,400	1,900	3,400	410	1,000	1,000		1,300			7,100
Ammoscalaria pseudospiralis	.4	3	.6	2	1	2	8																																	
Bolivina albatrossi									.4	.6		1	9	11	14		12	2				6	2	4	9	11	3	5	4	7	7	8	6	5	10		10			1
B barbata		13	3	3	3	3		15	12	15	8	.9	1	2	.9		.6	4	2	6								.5												
B lowmani	.4	.3	.3	.3	.4			1	2	8	2	1	.7	1	2		.6	.5		.4			.9	.5	1	.3		2	.5	.6	1	2	1	.8	.4		.9			
B ordinaria								2	1	3	3	3	3	3	5		4	1	2	.7		13	14	8	9	11	11	10	6	13	18	15	7	3	4		10			14
B striatula spinata		4	2		.4	2		.3		.3												.6																		
B subaenariensis mexicana		1	.9	.6	1	2		40	21	15	13	6	.7	11	5		9	13	13	9		.6		1	1	5				1		.5		.2	.8		.3			
B subspinescens									.8		.4	3	1	1	.3				.3			.6			1	3	.4		1	1	.8	.9	1	.4	.2		.6			.6
Bulimina aculeata																						.6					14	5	2	.6			2	4	.4		.5			12
B alazanensis																						3	.9	2				3	1	4	3	4		4	5		9			3
B marginata		15	8	4	9	5		20	15	6	8	12	13	3	4		10	23	22	31		.6		2	2	1														
B spicata													1											1	.3	.3	4						.7	1	1		1			.1
B striata mexicana									1	.3	.4	.4	12	5	4		2	1	1	.7		3	6	4	.5	.3	13	4	5	4	2	2	5	6	3		1			.7
Buliminella cf bassendorfensis		32	17	30	22	34			.2	3																		1												
Cassidulina carinata								.2	1					3	3		3	1		.7		4	30	10	5	2		17	49	6	3	2		13	2		.9			9
C curvata								.5	2	3	2	2	2	2	2		3	.5	2			7		2	1	2	.4				.4									
C neocarinata								.5	1	4	6	6	.7	3	4		2	1	2				3	1	2	2	.8	.5			.4		.2							1
C subglobosa			.6					.3	.4	3	3	1		3	1		.9	.3	1	.4		2	.4	5	1	1		8	3	6	9	8	.2	4	8		11			17
Cibicides aff floridanus		.3						2	15	9	16	9	4	11	9		11	3				.6	3	2	1	2	4	2	1	3	3	4	3	5	8		5			2
Elphidium spp		.3											.7				.3																							
Epistominella exigua														.2								1		1			7	7	4	12	15	19	4	5	5		6			2
E rugosa														.2			.3						.4	2	3	5						.9		2	1		.9			.5
E vitrea	.4	16	31	30	42	23		.3	.4	3	1								.3			.6																		
Eponides regularis								6	8	6	6	1	2	4	.9		7	37	34	36		.6	.9	1	.7	1	2													.1
E turgidus																						2		.5			4	3	2	6	2	.9	.5	.6	5		3			8
Globobulimina affinis											3	.4	.2														.4	.5			2		2	1	1		1			.2
G mississippiensis		.7	.3	1	2	.4		2	1										.3																					
Gyroidina orbicularis													.2				.3					.6	2			.3					2	.5		.4	2		2			.6
Gyroidinoides altiformis									.6		.8			.5	.9		.3	2	2			.6	.9	.5	.5	2			.5	.6	.4	.9		.2	.4		.2			1
Goesella mississippiensis	3						53														3																			
Lagenidae		.2	.3					1	1		2	2	2	1	.9		.9		2	2		2	1	1	2	2	.4	2	2	1	1	3	1	1	1		1			1
Miliolidae			1	.6		.9		.4	1	2	1	1													2	.9		.5			.8	.5		.2						.2
Nonionella atlantica		.7		.3																							.4													
N. opima			.3	.3	.4			1	1		.4		.2				.6																							
Osangularia cultur																											.4	2		4	2		5	6	6		3			
Planulina ariminensis															.3							1		3	3	.3						2		.2			.3			.6
P foveolata									1	.6	3	3	.2	.5	2		2	.6				1																		
Pullenia spp.									.6		1	.4	.7	1	.9		1	.2				3	1	2	1	.6	.4	2		.6	1	1		.2	.4		.3			.8
Rectobolivina dimorpha																								.5								.5								
Robulus spp		4	.6	.8	.4			.3	1	1	3	3	3	3	4		3	.6					1	1	1	.9			.5	.6					.2		.3			.3
"Rotalia" translucens													.2	3	4		2	5	11	7		14	17	14	21	27		6	4	10	8	7		10	11					12
Rotamorphina laevigata								.2				2														.6	.4	1			2	.9	.2	1	.8		1			1
Sigmoilina distorta								.7	.8	.3	.8	2		.2										.5	.3															
Siphonina pulchra									.2	.3		3					.3							1	1															
Sphaeroidina bulloides								.2	1	.6	1	2	8	4	3		2	.3	.9	1		6	4	5	7	3	8	2	2	3	5	2	8	6	4		5			.8
Textularia earlandi	61						.9														11						2						9							
Trifarina bradyi																						.6		1	.7						.4				.6		.2			.2
Uvigerina laevis								.7	2	3	3	9			.3		.6		.9					.5		.9														
U. parvula		6	33	27	18	26		2	4	3	8	7		.9			12	2	.3																					
U. peregrina													16	18	25		5	.3				17	1	14	11	7	6	7	7	8	5	6	12	12	13		16			4
Valvulineria mexicana		.3	.3					.2	.2	.9	1	.4	4	.9	.6			.3	.6	.4		.6	2				2		1				.2	.2	.4					
Virgulina mexicana														.5	.3									.5			.4	.5	.5	.6	.8	.5		.2	.2		.2			
V tessellata																									.3							.9	2		.2					.3
Other species	35	3	1			2	38	3	3	8	3	19	13	3	3		4	1	3	5	86	8	9	9	12	8	16	9	4	8	5	7	30	7	5		8			6

planktonic forms are treated as separate populations, with each constituting 100%. Total populations are estimated for each sample, since they all contained approximately the same amount of sediment, with a few exceptions. Results of the faunal analyses are on Tables II–IV. Only the more common and/or important species are included in these lists; detailed analyses are on file at the Marine Foraminifera Laboratory.

Detailed faunal analyses were made on only a few samples from each core, but each sample was examined to ascertain whether or not there was a faunal change. Faunas in surface sediment samples from the stations along this traverse, collected with a small coring tube, have been analyzed by PARKER (1954). Population data from some of these samples are included for comparative purposes, since the top sample from a long core may not represent the actual surface sediment due to methods of collecting and processing.

The following should be consulted for illustrations, descriptions, and additional distributions of the species listed in the present report: PHLEGER and PARKER (1951), PARKER (1954), PHLEGER. PARKER and PEIRSON (1953), and PHLEGER (1954).

CORE FAUNAS

In a previous study of core faunas from the northwestern Gulf of Mexico (PHLEGER, 1951) it was possible to differentiate an " upper " and " lower " core fauna based on the assemblages of planktonic Foraminifera. The upper planktonic fauna is the modern one and has the following general composition:

30–70%
    Globigerinoides rubra (d'Orbigny)

10–20%
    Globigerina bulloides d'Orbigny
    G. eggeri Rhumbler
    Globorotalia truncatulinoides (d'Orbigny)
    Pulleniatina obliquiloculata (Parker and Jones)

5–10%
    Globigerinoides sacculifera (H. B. Brady)
    Globorotalia menardii (d'Orbigny)

<1–5%
    Globigerinella aequilateralis (H. B. Brady)
    Globigerinoides conglobata (H. B. Brady)
    Globorotalia tumida (H. B. Brady)
    Orbulina universa d'Orbigny

The planktonic fauna which is widespread in lower sections of most northwestern Gulf of Mexico cores differs in having many or all of the following species absent or lower in frequency:

Globigerina eggeri Rhumbler
Globigerinella aequilateralis (H. B. Brady)
Globigerinoides conglobata (H. B. Brady)
Globorotalia menardii (d'Orbigny)
G. truncatulinoides (d'Orbigny)
G. tumida (H. B. Brady)
Orbulina universa d'Orbigny
Pulleniatina obliquiloculata (Parker and Jones)

(942)

In addition, the following occur in the lower fauna:

Globigerina inflata d'Orbigny
G. pachyderma (Ehrenberg)
Globorotalia punctulata (d'Orbigny)
G. scitula (H. B. Brady)

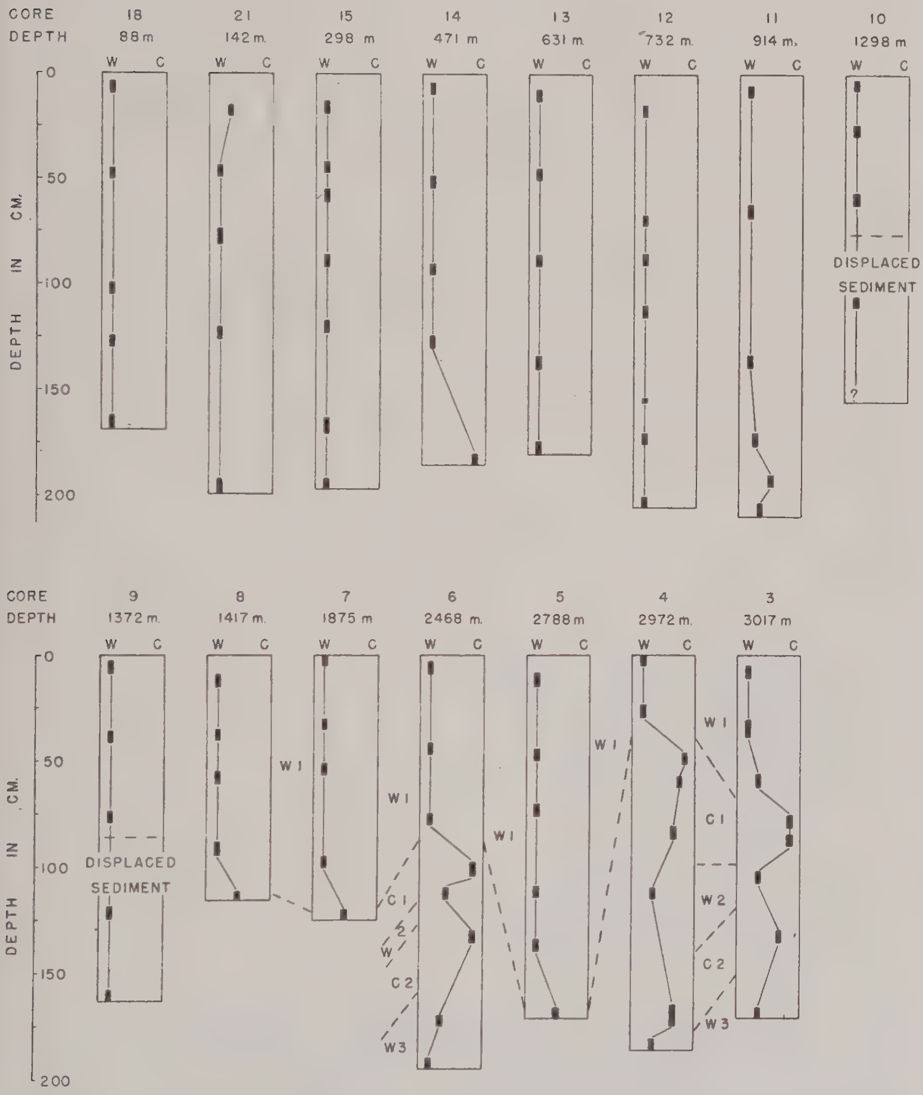

Fig. 3. Relative temperatures indicated by Foraminifera in the cores. W, relatively warm surface water. C, relatively cold surface water

The present cores contain " upper " and " lower " faunas which are comparable in species composition to those previously reported, with the following exceptions: in the upper, modern assemblage *Globigerinoides sacculifera* generally is more abundant especially in the area farthest off shore, *Globorotalia truncatulinoides* may be less abundant, and *Globigerina eggeri* may be more abundant; in the lower fauna, *G. inflata* and *G. pachyderma* are less common, being recorded in very low frequencies from only occasional samples.

The " upper " planktonic core fauna contains the modern assemblage and is assumed to represent conditions similar to those obtaining today, and may be considered to represent relatively warm surface water. The " lower " fauna contains fewer North Atlantic low-latitude planktonic specimens and consequently more mid-latitude forms, and is considered to represent a time of cooler surface water. Interpretation of these distributions may be clarified by examination of the data and discussion in PHLEGER *et al.* (1953) on distributions of North Atlantic planktonic Foraminifera.

Lower, colder-water faunas were present in eight of the fifteen cores examined. The interpretations of the faunas are summarized in Fig. 3, and the faunas on which these interpretations are based are listed in Tables II–IV. Cores 3, 4 and 6 contain two cold-water faunas separated by a warm-water fauna and their lower sections contain an additional warm-water fauna. Cores 5, 7, 8, 11 and 14 contain a cold-water fauna in their lowermost sections. The other cores contain the modern Gulf of Mexico planktonic fauna throughout their entire lengths. Core 18, on the lower continental shelf at a depth of 88 m, contains few planktonic specimens.

The benthonic Foraminifera in most of the core samples are normal for the water depths at which the cores were collected (see PHLEGER, 1951, Figs. 22–25; PARKER, 1954, Figs. 3–9). Striking exceptions occur in cores 9 and 10. In core 9, from 1372 m depth, the bottom sample at 158–163 cm contains the following shallow-water (continental shelf) species in significant frequencies:

Angulogerina bella Phleger and Parker
Bolivina barbata Phleger and Parker
B. striatula spinata Cushman
Bulimina marginata d'Orbigny
Buliminella cf. *bassendorfensis* Cushman and Parker
Elphidium spp.
Globobulimina mississippiensis F. L. Parker
Nonionella opima Cushman
Rectobolivina advena (Cushman)
" *Rotalia* " *beccarii* (Linné) variants
Virgulina pontoni Cushman

A few of these species occur in lower frequencies from 145–158 cm, and single specimens of *Bolivina striatula spinata*, *Buliminella* cf. *bassendorfensis* and *Liebusella* sp. occur at 3–8 cm in the core. Most of the benthonic Foraminifera in this core are normal for the depth at which the core was collected. Quartz grains of fine sand size and wood fibres which are coloured dark brown occur from 85 cm to the bottom of the core.

(944)

In core 10 from a depth of 1,298 m the following shallow-water species are important constituents of the bottom core section at 144–155 cm:

Bolivina pulchella primitiva Cushman
B. striatula spinata Cushman
Bulimina marginata d'Orbigny
Buliminella cf. *bassendorfensis* Cushman and Parker
Cibicidina strattoni (Applin)
Elphidium spp.
Nonionella opima Cushman
" *Rotalia* " *beccarii* (Linné) variants
Virgulina pontoni Cushman

A few specimens of *Buliminella* cf. *bassendorfensis* also occur at 56·5–61·5 cm and 2·5–7 cm. Plant fibres and fine quartz sand occur in the samples from 75 cm to 155 cm. The major part of the benthonic fauna consists of species normal for the depth of the core.

Twenty-six specimens of *Gümbelina* are recorded from the lowermost section of core 10.

Occasional shallow-water benthonic Foraminifera are recorded from the following additional deep-water cores of this series: 3, 4, 5, 6, 7, 8, 13 and 14. These are single specimens and no sample contains more than four specimens, while many contain none. No other evidence of displacement of sediment was observed.

DISCUSSION

Interpretations of the core planktonic Foraminifera in terms of " warm " (like the present) and " cold " (colder than present) surface water temperatures are given on Fig. 3. In this figure, " W 1 " refers to the modern warm-water fauna, " C 1 " to the last cold-water fauna, " W 2 " to the preceding warm-water fauna, etc. It is suggested that these stages can be correlated in the present cores, as shown on Fig. 3, especially where a succession of such faunal variations occurs and where there is no indication of displaced sediment. This is especially striking in comparing cores 3, 4 and 6. These cores came from the same relatively small area and from similar depths in the eastern Gulf of Mexico basin. Each of them has three warm-water faunas separated by two cold-water ones, and these occur within approximately the same thickness of sediment.

It is suggested that these warm and cold faunas also are to be correlated with similar successions described previously from northwestern Gulf of Mexico cores (PHLEGER, 1951, Figs. 29–33). The cold-water faunas have been interpreted elsewhere as representing Pleistocene glacial stages and/or substages and the warm-water faunas are thus possible interglacial stages and/or substages. The widespread occurrence of a cold-water fauna beneath the modern fauna in this region suggests a general cooling of Gulf of Mexico surface water during the last glacial or stadial stage.

Correlation of the planktonic faunas makes it possible to estimate the amount of post-glacial sedimentation along this traverse. This is based on the assumption that the upper, warm-water fauna represents post-glacial deposition. The amounts of deposition appear to be approximately as follows:

Core	Water depth in m	Estimated post-glacial deposition in cm
3	3017	65
4	2972	40
5	2788	170
6	2468	90
7	1875	120
8	1417	115
9	1372	>150
10	1298	>150
11	914	>210
12	732	>205
13	631	>180
14	471	155
15	298	>195
21	142	>195
18	88	>165

Some useful generalizations may be made from these data. The amount of post-glacial deposition is smallest away from the major source of supply, the Mississippi River, and near the centre of the basin; there is a general increase in amount of deposition closer to the source, as expected. In all but one core shoaler than 1,400 m the coring tube did not penetrate through post-glacial sediment. There is considerable local variation in the amount of post-glacial deposition. For example, in core 5 in the basin there is two to four times as much post-glacial deposition as in nearby cores from similar depths. Core 14 on the upper part of the continental slope has considerably less post-glacial sedimentation than nearby cores at similar depths and position. The amount of post-glacial deposition in the cores from the basin and lower continental slope in the present cores is comparable to that shown in cores from the basin and lower slope reported previously from the northwestern area (see PHLEGER, 1951, Figs. 29–33). The amount of such deposition on the upper slope appears to be larger than in the western area, although there are exceptions.

Cores 9 and 10 contain sediments and faunas in their lower sections which appear to have been displaced downslope from shoaler depths, presumably in the form of turbidity currents. The presence of abundant sand, wood fibres and abundant shallow-water benthonic Foraminifera at water depths of 1,298 m and 1,372 m appears to be conclusive evidence for such displacement. Most of the benthonic Foraminifera are species normal for the depth at which the core was taken; this demonstrates that the displaced material was deposited at the present water depths at those stations. The age of the displacement is post-glacial (W 1), as shown on Fig. 3.

Cores 9 and 10 occur in the bottom of Mississippi Canyon (Fig. 2). Other cores in this traverse do not have displaced sediment, at least in significant amounts, and these are located on topography other than the canyon floor. This suggests that the turbidity flow was localized in the canyon. Studies by SHEPARD (1951) and LUDWICK (1950) in the San Diego area have shown that displacement of sediment from shallow to deep water appears to be funnelled down the canyons in that area, and it seems probable that much displaced sediment flows down the channels of submarine canyons in other areas of the world. The restriction of displaced sediment to the Mississippi Canyon floor in the present cores is evidence in this connection.

The lower section of core 15, below approximately 165 cm, contains abundant sand grains and plant fibres; this sediment contains no benthonic Foraminifera which are characteristic of water shoaler than that at which the core was collected (298 m). It is possible that this sediment was displaced from shallow water, but the absence of displaced Foraminifera suggests that a turbidity current was not the mechanism of deposition. It appears more likely that this material may be river sediment which was carried offshore (approximately 20 miles) during flood stages of the Mississippi River. Shallow-water Foraminifera would not be expected under these conditions.

It is suggested that the occasional specimens of shallow-water Foraminifera found in cores 3–8 and 13–14 do not indicate the presence of appreciable amounts of displaced sediment in these cores. These specimens may have been deposited by one or more of the following mechanisms:

(1) They may have been carried somewhat beyond the limit of turbidity flows because of slow settling velocity or low effective specific gravity. If the specimens contained protoplasm this mechanism would be aided.

(2) They may have been put in suspension by wave action when they contained protoplasm, and were carried to their present positions by currents. A few specimens of living, shallow-water benthonic Foraminifera have been reported in offshore plankton tows in the northwestern Gulf of Mexico (PHLEGER, 1951, p. 36).

(3) They may have been deposited by several very small-scale turbidity currents which transported small amounts of sedimentary materials.

The presence of specimens of *Gümbelina* in core 10 is difficult to explain. These may have been carried out by the river and deposited at their present position, or they may possibly be contaminated by a salt plug bringing early Tertiary or Cretaceous sediments to the surface.

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Reprinted from PACIFIC SCIENCE, *vol. IX, no. 4, October, 1955*

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Distribution of Black-footed Albatross, *Diomedea nigripes*, off the West Coast of North America, 1949 and 1950[1]

J. L. McHugh[2]

SINCE THE OCEANOGRAPHIC SURVEYS of the California Cooperative Sardine Research Program began in March 1949, records have been kept of the numbers of albatrosses seen at each station. At monthly intervals the ships have covered an area approximately 1,300 miles long by 400 miles wide. The patterns of stations occupied, differing somewhat from cruise to cruise, and altered considerably in 1950, have been figured by McHugh (1950), Anonymous (1950), and McHugh and Ahlstrom (1951).

These albatross observations have formed a part of the objective, conceived early in the development of the research program, to study as many phases of the biology of the region as possible. Felin and Marr (1951) already have pointed out the importance of these subsidiary investigations in relation to the main purpose of the sardine program.

INDICES OF ABUNDANCE

Usually, counts were made shortly after the ship hove to at each station, and again just before departure. The second count commonly, but not always, exceeded the first (McHugh, 1950). The indices of abundance used here are based on the maximum numbers of birds observed at each station. For obvious reasons, no record was made at stations occupied during darkness, although albatrosses sometimes were seen at night (McHugh, 1952).

It is believed that several factors other than relative abundance may influence the counts. Birds may follow a ship as it cruises between stations, but it is not believed that the Black-footed Albatross travels great distances in this way (Miller, 1942; Thompson, 1951). The tendency to congregate about the motionless vessel may vary with weather conditions, especially if the frequency and duration of soaring flight is related to wind force, although an attempt to analyse the data along these lines produced no clear-cut relationship. Furthermore, counts may tend to increase during the day (McHugh, 1950) or when the ship is in an area for longer periods (Yocom, 1947). The visual acuity of birds and observers is affected almost certainly by atmospheric conditions and wind. The many observers undoubtedly varied in interest and in acuteness of vision. For these reasons, counts at adjacent stations were averaged by dividing the survey area into 21 blocks, by a grid of three blocks east to west and seven north to south (Fig. 1). These blocks are not equal in area, for the species seldom approaches within sight of shore, and often is not present in great numbers at the inshore stations. To avoid masking the reduced abundance near shore, the seven inshore blocks were chosen as far as possible to in-

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[1] Contributions from the Scripps Institution of Oceanography, New Series, No. 805. Manuscript received February 10, 1955.

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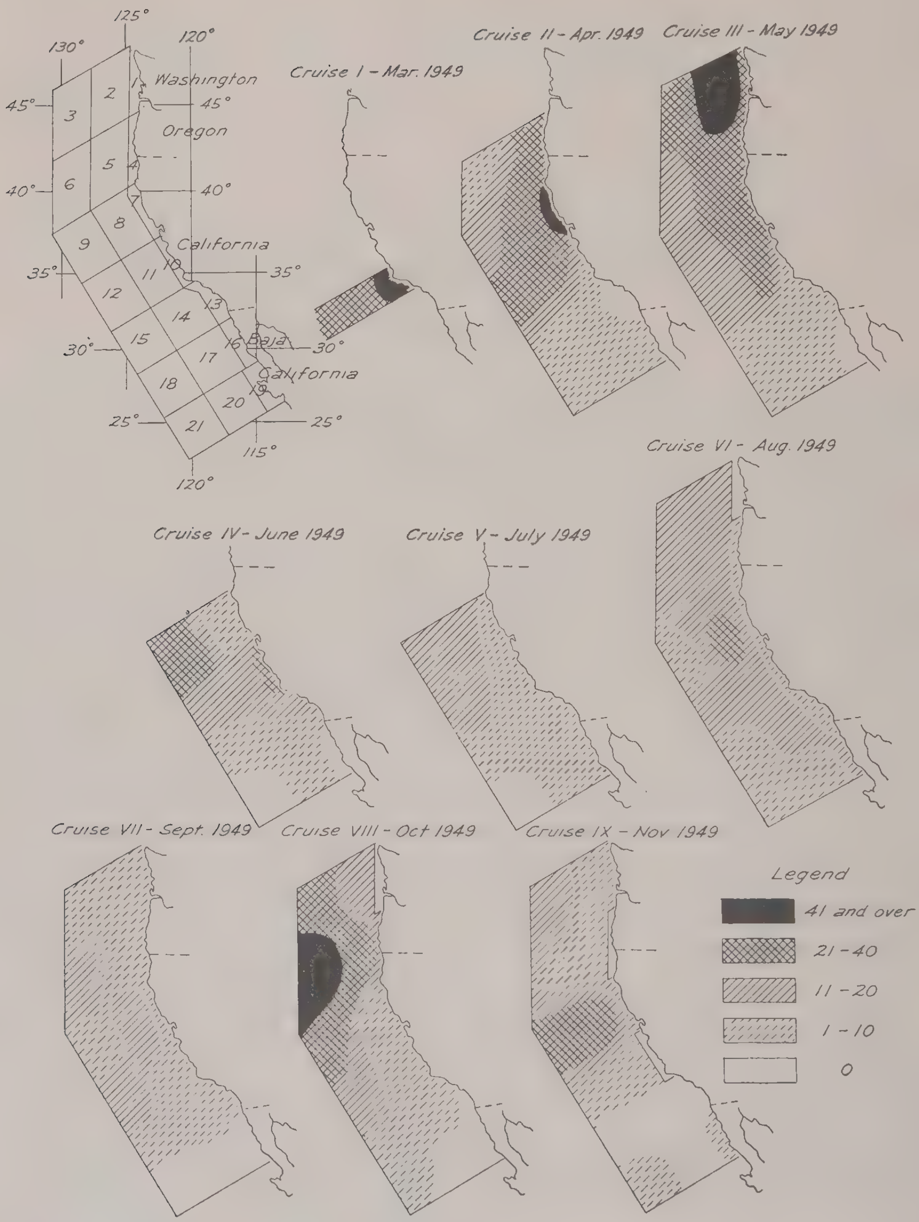
125°
130°
120°
Washington
45°
45°
Oregon
40°
40°
California
35°
35°
Baja
California
30°
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25°
25°
115°
120°
1
2
3
4
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8
9
10
11
12
13
14
15
16
17
18
19
20
21
Cruise I - Mar. 1949
Cruise II - Apr. 1949
Cruise III - May 1949
Cruise IV - June 1949
Cruise V - July 1949
Cruise VI - Aug. 1949
Cruise VII - Sept. 1949
Cruise VIII - Oct 1949
Cruise IX - Nov 1949
Legend
41 and over
21 - 40
11 - 20
1 - 10
0

FIG. 1. Locations and numbers of blocks from which indices of albatross abundance were derived in 1949 and 1950 (upper left), and distribution of Black-footed Albatrosses over the survey area during 1949. The contours were drawn according to the average numbers of birds per station in each block.

clude only the inshore stations on each line. Their offshore limit is a line running roughly parallel to the coast about 40 nautical miles westward of the major promontories. The second series of blocks extends from the western boundary of the first and has a width of about 160 miles east to west; the third is approximately equal in width to the second. Each of the seven inshore blocks, about 9,600 square nautical miles, is roughly one-quarter the average area of the remainder. The inshore blocks each contained two stations in 1949, and an average of six in 1950; each offshore block contained an average of nine stations in each year.

As a monthly index of abundance, all counts within each block were averaged, a process designed to minimize many of the most serious sources of error. These indices may be defined as representing the best available estimate of relative monthly abundance within each block. There is little point in expanding these estimates into a measure of the total number of birds present in the area, for there is no adequate basis for determining the absolute density of birds per unit area that each count represents. Assuming, however, that all birds within a ten-mile square collect around the ship while it occupies a station, the total number of Black-footed Albatrosses present within the region surveyed in May 1949, the month in which most birds were observed, was close to 100,000. This estimate is not inconsistent with the results of the census made by Fisher (1949) on the Island of Midway.

The cruises have not always covered the entire region included within the station pattern. Sometimes parts of the area have been missed on account of adverse weather conditions or mechanical breakdowns. Sometimes the station coverage has been shifted according to plan, in response to seasonal changes in the location of sardine spawning. Blocks 7 to 18 inclusive were occupied on most cruises in 1949 and 1950, and it is possible to calculate an index of abundance for the waters off the California coast by summing the indices for these blocks (Table 1). However, it would be advantageous to discover a more restricted area that would reflect the abundance of birds equally well. Block 11 was chosen because it is sufficiently far north to contain relatively large numbers of albatrosses, yet close enough to an important sardine spawning area that it may be expected to be traversed on most, if not all, cruises. A high and statistically significant coefficient of correlation was obtained between the monthly indices for block 11 and for the larger area exclusive of block 11 (r = +0.863, P much less than 0.01). In view of the many possible sources of error to which these indices are subject, it is concluded that the relative abundance of birds in block 11, lying west of Point Conception, is indicative of the relative abundance off the entire California coast.

TABLE 1

Indices of Abundance of Black-footed Albatrosses in the Region Covered by Blocks 7 to 18 Inclusive

MONTHS	INDICES OF ABUNDANCE	
	1949	1950
February	...	63
March	...	113
April	132	66
May	106	74
June	86	87
July	60	62
August	78	61
September	46	25
October	66	...
November	59	...

GENERAL DISTRIBUTION

Thompson (1951) has observed *Diomedea nigripes* as far south as 15° 40′ N. in the Central Pacific. Along the west coast of North America, however, the species has never been observed in great abundance south of Cedros Island, off the coast of Baja California. Al-

(951)

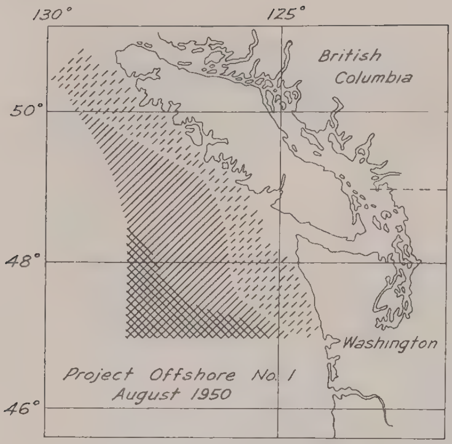

FIG. 2. Distribution of Black-footed Albatrosses off the British Columbia and Washington coasts in August 1950. Legend as in Figs. 1 and 3. The contours were drawn according to the numbers of birds at each station.

though Cruise 20, in November 1950, extended the coverage southward almost to 20° N., no albatrosses were seen at this time off the entire Baja California coast. Later cruises, reaching this latitude in all seasons, may be expected to define more accurately the southern extent of the species range.

To the northward, the Black-footed Albatross is common off British Columbia and Alaska, and has been seen irregularly in the Bering Sea (Kenyon, 1950). Counts supplied through the cooperation of Dr. J. L. Hart and R. J. Waldie from off the coasts of Washington and British Columbia in August 1950 range from 1 to 24, and average 13 birds per station (Fig. 2).

To the westward, in 1949 and 1950 only one cruise extended more than about 400 miles offshore. On this cruise, numbered 18, in September 1950, the maximum count in the region outside the grid defined in Figure 1 was six birds at station 70.220. *Diomedea nigripes* is found across the entire Pacific, however, for it breeds in the mid-Pacific islands in winter and spreads over the north Pacific at other seasons.

SEASONAL DISTRIBUTION AND ABUNDANCE

In 1949 and 1950 Black-footed Albatrosses were about twice as abundant in the survey area over the period March to May as in any other month. The distribution of counts in 1949 (Fig. 1) suggests that the decrease in abundance in the summer months is caused by a general northerly migration, for the greatest density of birds was encountered off Point Conception in March, off San Francisco in April, and off the Columbia River in May, an average northward shift of about 300 nautical miles per month. Not until October did similar concentrations appear again within the survey area, this time in a region well offshore from Cape Mendocino. In 1949 also, there appeared to be a general shift of the population from inshore in spring to offshore in fall.

In 1950 (Fig. 3) there were less definite indications of a progressive northerly migration, although the index of abundance was highest in March. If a northward movement did take place, it probably occurred earlier than in 1949, and there is some evidence that the return movement began in May, for the birds were more abundant off Cape Blanco in May, and off San Francisco in June than at any other period in 1950. Furthermore, in July and August the greatest densities were observed in the region between San Francisco and Point Conception. The 1950 season differed from 1949 also in that, from May to August inclusive, more birds were seen inshore and less at the offshore stations.

FACTORS AFFECTING ALBATROSS DISTRIBUTION

Variations in the numbers of *Diomedea nigripes* observed off the shores of North America have been attributed to various factors. Miller (1940) found these birds concentrated over a "cold tongue" of sea water, rich in nutrients and plankton. Thompson (1951) reported that the species was more abundant east of the 135th meridian, and showed that the increasing numbers of birds seen between

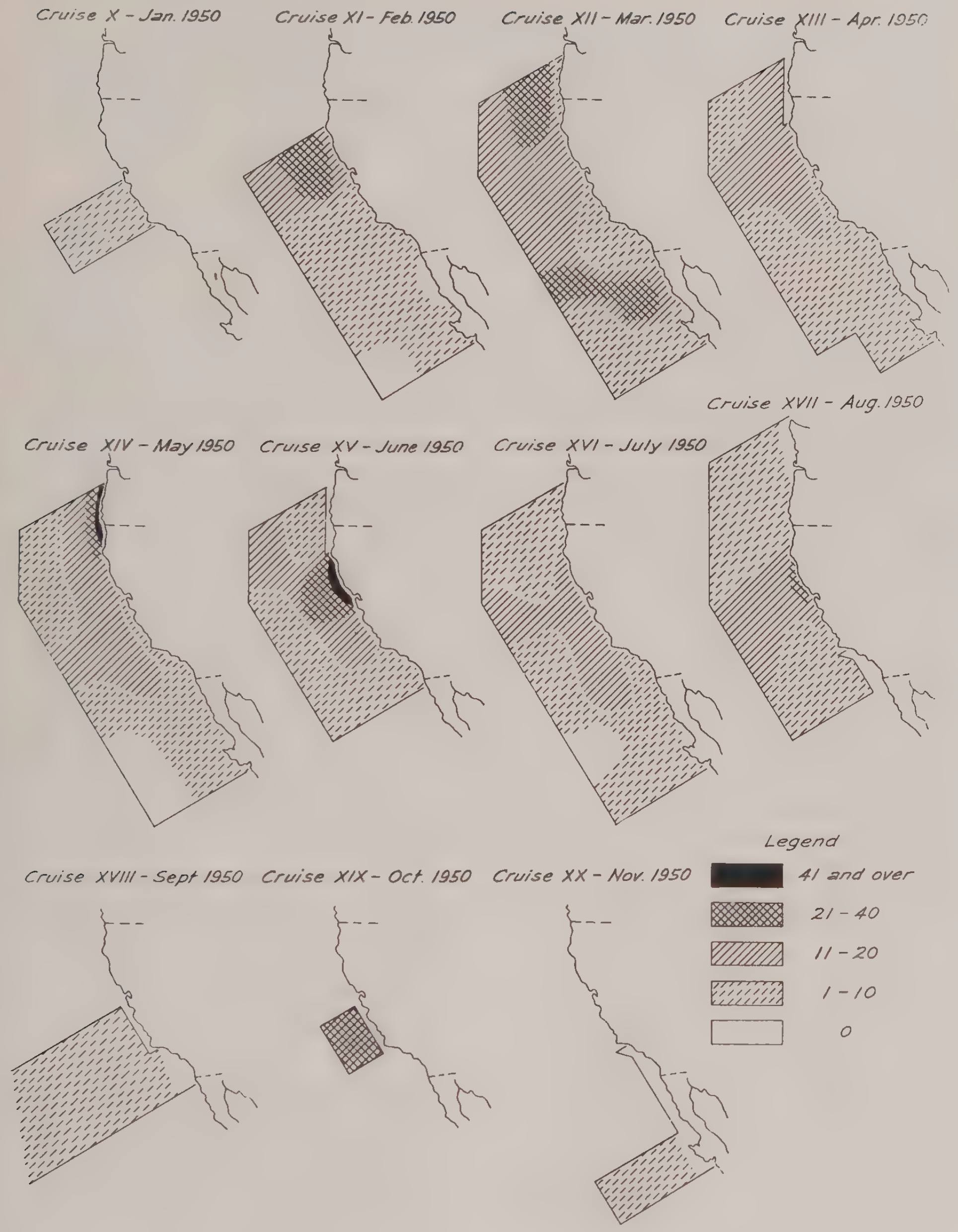
Cruise X - Jan. 1950
Cruise XI - Feb. 1950
Cruise XII - Mar. 1950
Cruise XIII - Apr. 1950
Cruise XVII - Aug. 1950
Cruise XIV - May 1950
Cruise XV - June 1950
Cruise XVI - July 1950
Legend
Cruise XVIII - Sept 1950
Cruise XIX - Oct. 1950
Cruise XX - Nov. 1950
41 and over
21 - 40
11 - 20
1 - 10
0

FIG. 3. Distribution of Black-footed Albatrosses over the survey area during 1950. The contours were drawn according to the average numbers of birds per station in each block.

TABLE 2

Average Albatross Counts and Plankton Volumes for Cruises 1 to 5

BLOCK NUMBERS	REGION	MEAN NUMBERS OF ALBATROSSES	MEAN VOLUMES OF PLANKTON
7–9	Northern Calif.	19	214
10–12	Central Calif.	20	141
13–15	Southern Calif.	4	65
16–18	Baja Calif.	2	48

this line and the coast were associated with decreasing sea temperatures. Thompson also noted a direct relationship between the numbers of jellyfishes, observed by luminescence in the ship's wake at night, and the numbers of albatrosses counted during the day. He reasoned that jellyfishes, and hence albatrosses, were most abundant in the colder, more productive waters.

No consistent relationship between the total plankton volume in a standardized net haul and the numbers of albatrosses seen at the same station was observed on the 1949 and 1950 cruises. In a general way, however, the blocks in which the highest average numbers of birds were recorded were those in which the greatest average plankton volumes occurred. As illustrated in Table 2, the numbers of albatrosses and the volumes of plankton per unit volume of water[3] were greatest off the northern California coast, and least off southern and Baja California. It is not known whether this association indicates a causal relationship.

It is tempting to search for relationships between the pattern of albatross abundance and the distribution of the various physical, chemical, and biological factors recorded at the hydrographic stations. The albatross counts presumably are not subject to the criticism that is levelled at counts of plankton and other marine organisms, namely, that they represent only the standing crop, for these birds are almost completely free from predation while at sea (Miller, 1940; Yocom, 1947; McHugh, 1952). Nevertheless, strong and apparently highly significant statistical correlations can be obtained even with random numbers by trial and error methods. Inasmuch as there is no good biological evidence to suggest that albatross abundance and any of the physical, chemical, or biological factors are related, no correlations were sought.

In former years, when it was more abundant, the Pacific sardine (*Sardinops caerulea*) performed an annual migration from California waters to summer feeding grounds off the Pacific Northwest, sometimes ranging as far north as southeastern Alaska. There is indirect evidence, particularly in the 1949 observations, that the Black-footed Albatross performs a similar seasonal migration northward along the coast. If such a migration does occur, it may be in response to similar stimuli. Continued study of the distribution and movements of these birds may provide valuable clues to the question of varying sardine abundance and availability.

SUMMARY

Counts of Black-footed Albatross were recorded at all stations occupied during daylight on cruises of the California Cooperative Sardine Research Program in 1949 and 1950. The survey area was divided into blocks, and the counts per station within each block were averaged to derive indices of abundance. Birds were most abundant off California and Baja California during the spring months, and

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[3] The plankton volumes were taken from an unpublished mimeographed summary prepared by the staff of the South Pacific Investigations of the U. S. Fish and Wildlife Service.

(954)

higher counts were recorded in the northern part of the region. There is some evidence of a northward migration along the coast in summer, similar to the summer migration of the Pacific sardine.

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ABSTRACT: *Methods employed for routine laboratory culture of foraminifera are described and some preliminary experiments concerning the effects of food, temperature and salinity upon the population growth are discussed. Populations of* Rotaliella heterocaryotica *Grell have been found to eat dead flagellate cells* (Chlamydomonas) *and living diatoms* (Nitzchia)*. Populations of* Rotaliella *sp. do not appear to utilize dead* Chlamydomonas *and will die unless living* Nitzchia *or its equivalent is provided. Temperatures of 14.5° C. result in a lower rate of growth for* Rotaliella heterocaryotica *and* Rotaliella *sp. than do room temperatures of 22.2° C. and 24.5° C. Data from salinity experiments on* Rotaliella heterocaryotica *suggest the following: There is no significant population growth at salinities less than approximately 25‰; population growth occurs at salinities above 25‰ with the optimal salinity apparently between 26 and 30‰; no consistent population growth occurs at salinities above approximately 37‰.*

Preliminary laboratory experiments on ecology of foraminiferal populations*

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INTRODUCTION

In the study of populations of foraminifera, numerous problems arise that are difficult to answer by field studies alone. Underlying causes affecting distribution may be so complex that the correlation of the usual ecologic factors (e.g., temperature, salinity, etc.) with observed distribution is only partially satisfactory. For example, the marked biofacies depth-boundary near the edge of the continental shelf has been attributed to the presence of a seasonal water-layer (Phleger, personal communication), which is subject to seasonal variations of temperature, salinity, light, food, etc. On the basis of field studies alone, however, it is difficult or impossible to determine which specific environmental factors are critical. If key species from above and below this biofacies depth-boundary could be cultured under controlled laboratory conditions, it might be possible to determine the relative importance of individual environmental factors. It may be possible to understand the effects of the numerous features of the marine environment on foraminifera by studying the physiological effect of single factors. After some understanding of single factors is gained, it should be possible to analyze the effects of combinations of factors.

Another important problem is the measurement of foraminiferal productivity, such as rates of growth and number of young produced per year. A knowledge of the rate of addition of empty tests of foraminifera to the sediments and of the conditions which affect this productivity are of primary interest in sedimentology. This problem and related ones may be partially answered by controlled population experiments. Various taxonomic problems, such as determination of specific ranges of morphological variation and correct identification of juvenile forms, could be simplified by study of laboratory cultures. Arnold (1954*a*) has illustrated this approach admirably in his study of variations in *Discorinopsis* cultures.

Many workers have cultured foraminifera in the laboratory, but it is only recently that more refined techniques have been used. Arnold (1954*b*) gives a brief historical summary of culture experiments on foraminifera in his paper on culture methods.

Preliminary work with cultures of benthonic foraminifera was started at the Marine Foraminifera Laboratory in the spring of 1954, as a part of long-range

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*Contribution No. 22, Marine Foraminifera Laboratory; Contribution from the Scripps Institution of Oceanography, New Series, No. 806.

micropaleontology, vol. 1, no. 4, pp. 351-358, text-figs. 1-3, october, 1955

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studies of foraminiferal ecology. The purposes of the present discussion are to describe the methods being used for the experimental culture of foraminifera, and to give the results of some preliminary laboratory experiments.

The work has been done under the direction of Fred B Phleger. Discussions with Zach M. Arnold have been of great value. Karl G. Grell, of the Max-Planck-Institut für Biologie, has aided greatly by suggesting culture techniques and procedures, and by furnishing cultures of *Rotaliella heterocaryotica* Grell, *Rotaliella* sp., and a marine species of *Chlamydomonas.* The studies have been supported in part by a contract of the University of California with the Office of Naval Research and in part by American Petroleum Institute Project 51.

METHODS

Suggestions for collecting shallow-water foraminifera made by Myers (1935) and more especially by Arnold (1954*b*) generally have been followed. Material has been transported to the laboratory in a thermos bottle kept slightly below the temperature of the original environment. If a small amount of organic material and a relatively large proportion of water are included, a considerable period of time may elapse before the samples are examined. Sediment samples from the Gulf of Mexico have been flown to La Jolla in thermos bottles, and the living foraminifera have appeared to be healthy upon arrival.

Arnold (1954*b*) has reviewed culture methods and has given suggestions on technique, particularly for intertidal forms. Special methods not required for some biological studies are necessary for controlled ecologic experiments, since all aspects of the environment should be known at all times. The culture should be free of other organisms which may influence the foraminifera. Associated animals may compete for the same food supply and may feed upon the reproductive products and upon the foraminifera themselves. Associated animals usually can be removed by repeated transfer of the specimens by pipette through several dishes of sterile sea water. In this way the larger unwanted organisms eventually will be eliminated, but specimens of foraminifera may still have micro-organisms attached to them; these are difficult to remove. Bacteria-free cultures are desirable, especially for critical nutrition studies, and an attempt should be made to make the culture as sterile as possible. Several methods have been devised for purifying other protozoans by use of antibiotics (Slater, 1955) and these techniques may prove useful in the present studies.

Pyrex custard-dishes with a bottom area of 28 cm.^{2} and a height of 40 mm. are used for starting stock cultures. The sides of these containers slope outward, giving a relatively large water-surface area. A 100 mm. petri-dish cover fits snugly over the top. These inexpensive dishes have the advantage of holding a sufficiently large volume of water; they are easy to examine under the microscope, and removal of attached foraminifera is facilitated because of the sloping side of the dish. Benthonic diatom food stocks are also grown in these containers, but 500 cc. Erlenmeyer flasks are more suitable for the green flagellates.

Some foraminifera cultured in our laboratory do not require living food, and with these forms the husbandry is relatively easy. Such species can be kept in "sterile" sea water, and suitable dead organic food added regularly from time to time. *Chlamydomonas* cells which have been killed by heating to 50° C. and then added to the culture form an "artificial detritus" on the bottom of the dish, upon which the foraminifera feed with apparent relish. At our laboratory the cultures are fed twice weekly. The amount of food varies with several factors and must be determined by experiment for each species and for each culture. Too much food will result in excessive bacterial activity, and too little food will not provide for optimum growth of the species.

If the foraminifera will eat only living material, this can be provided most easily by feeding them diatoms or flagellates, either grown in the same culture or regularly provided from another culture. Suitable algal food cultures may be easily maintained in the laboratory. Arnold (1954*b*) has given a recipe for Föyn's "Erdschreiber" similar to that used in our laboratory for the culture of these food stocks. It is necessary to have a varied supply of diatoms and flagellates, particularly for nutritional experimentation. These may be cultured from species found in the original sample along with the foraminifera, or they may be from standard laboratory culture stocks.

The writer maintains cultures of *Chlamydomonas, Platymonas, Amphidinium, Nitzchia,* and several species of *Navicula,* as well as several other unidentified forms, for food supply. Each stock culture should be subcultured at intervals so that degenerative changes will not occur. Infrequently used cultures can be kept refrigerated under dim light so that subculturing can be postponed for much longer intervals. Routine stocks of food materials may be kept at higher temperatures and under more intense illumination to obtain maximum production.

A proper balance is essential between amount of food and the size and type of foraminiferal population. Although this balance often is maintained in impure cultures because of the interreactions of other organisms, many "pure" cultures are difficult to balance. The diatoms may reproduce so rapidly that they inhibit growth or even kill the foraminifera. Practical control in experimental cultures is possible through changes in the light intensity and/or concentration of mineral nutrients.

The other environmental conditions should be kept near the normal values encountered by the cultured species in its natural habitat. Temperature must be kept between the upper and lower reproductive limits of the species concerned. In some forms this range is narrow, whereas in others it may be very wide. At temperatures outside the reproductive temperature limits, the foraminifera may remain alive and yet not reproduce.

An accurate census of the population can be made only by a total count of all culture individuals at a given time. This is not practicable for large populations, and a more rapid sampling technique was devised. It was observed that the foraminifera tend to become evenly distributed in the culture container even though they may have been irregularly grouped at first. The projected area of 13 mm.^{2} formed by a Whipple counting reticle 3.6 mm. on a side at 20× magnification was selected as a unit area for the sampling procedure. By scribing marks at various points on the dish, the reticle could be aligned so that the same areas could be counted at different times. The average population of a number of such areas gives a measure of the culture, expressed as numbers of individuals per unit area.

Three types of temperature control were used. The lowest temperature, 14.5° C., was regulated by a constant-temperature refrigerator, while the other two "room temperatures" varied according to their location in the laboratory. Cultures fed with living *Nitzchia* were placed on a shelf near the window, where a thermograph recorded an extreme range of 18.0° to 30.0° C., with a mean of 24.5° C. Forms fed on dead *Chlamydomonas*, on the other hand, were kept in a darkened cabinet, close to the floor and as far away as possible from large-scale temperature fluctuations. In this location the temperature ranged from 19.0° to 26.0° C., with a mean of 22.2° C.

Salinities higher than that of normal sea water were obtained by evaporating La Jolla sea water of 33.5‰ salinity to one-half its original volume and then diluting the product with distilled water until the desired salinities were obtained. Lower salinities were obtained by dilution with distilled water.

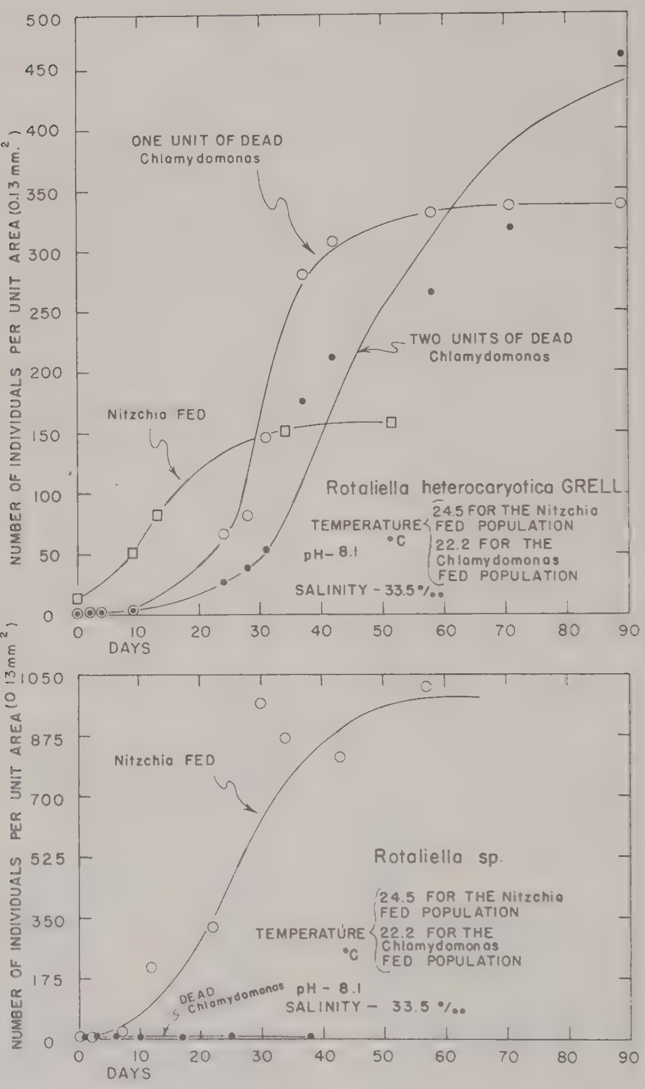
Experiments were made on *Rotaliella heterocaryotica*, a very small species from the intertidal zone at Rovigno, Yugoslavia, and on *Rotaliella* sp. from the intertidal zone at La Jolla, California. The normal development of *Rotaliella heterocaryotica* is now well known (Grell, 1954). Its life cycle consists of an alternation of sexual (gamont) and asexual (agamont) generations. In *R. heterocaryotica*, the two stages are morphologically indistinguishable and can be differentiated only by cytological methods. The gametes of the sexual gamonts are amoeboid, and their fusion occurs within the same parent test. Fusion results in the formation of from five to twelve young agamonts, the number produced presumably depending upon environmental conditions. After approximately two weeks' growth, the six-chambered agamont has reached its adult size of approximately 60μ and reproduces again. Reproduction of the agamont involves the formation of twelve agametes which develop into the gamonts of the sexual generation. Approximately two weeks later, the 60μ gamonts consist of five chambers, at which stage the gametes are again produced and the cycle is complete.

Rotaliella sp. is similar to *R. heterocaryotica* and is the same size, but differs from it in several characters. The life cycle is not known in detail but presumably is comparable to that of *R. heterocaryotica*.

EXPERIMENTAL RESULTS

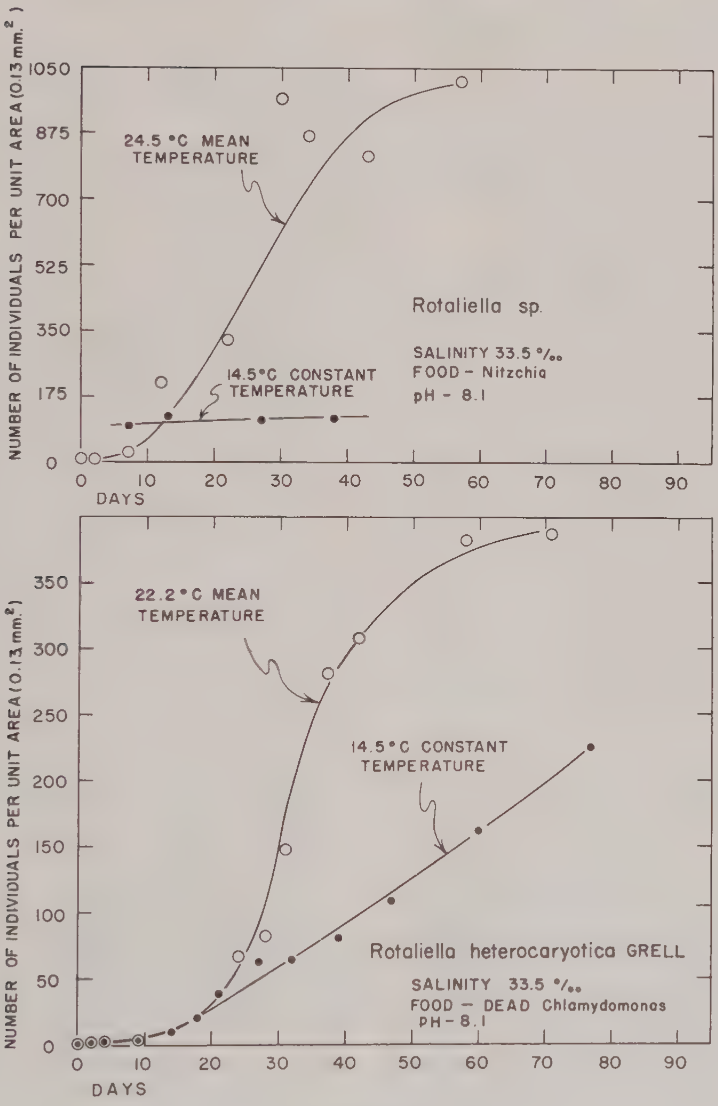
Food requirements: Text-figure 1 summarizes observations on cultures of *Rotaliella* sp. and *R. heterocaryotica* fed living *Nitzchia* and varying amounts of dead *Chlamydomonas*. Examination of text-figure 1 shows:

1. *Rotaliella heterocaryotica* apparently can utilize both dead *Chlamydomonas* cells and living *Nitzchia*, whereas *Rotaliella* sp. appears to be unable to feed upon dead *Chlamydomonas* and must have living *Nitzchia* or its equivalent for population growth.
2. *Rotaliella heterocaryotica* populations fed twice the concentration of dead *Chlamydomonas* grew at a lower initial rate, which later approached the growth curve of the population fed with one unit concentration of food.
3. *Rotaliella heterocaryotica* populations fed with one unit concentration of dead *Chlamydomonas* had a population maximum of approximately 320



TEXT-FIGURE 1

Growth of laboratory populations of *Rotaliella* sp. and *Rotaliella heterocaryotica* Grell when fed different food materials.



TEXT-FIGURE 2

Growth of laboratory populations of *Rotaliella* sp. and *Rotaliella heterocaryotica* Grell at two temperatures.

per unit area. On the other hand, *R. heterocaryotica* populations fed twice the concentration of food appeared to be capable of populations higher than this.

Temperature experiments: Text-figure 2 shows the rate of population growth of *Rotaliella heterocaryotica* and *Rotaliella* sp. cultured at two different temperatures. Cultures maintained at 14.5° C. showed much lower rates of population growth in both species than did those grown at room temperatures (22.2° C. and 24.5° C. mean temperatures).

Salinity experiments: Rotaliella heterocaryotica cultures were prepared using sea water of eleven different salinities, 16.8, 20.1, 23.5, 26.8, 30.2, 33.5, 40.2, 46.9, 53.6, 60.3, and 67.0‰. These cultures were then allowed to evaporate as the experiment progressed. On the fifty-second day, distilled water was added to replace that lost by evaporation (10 cc.) and the salinities at this time were calculated. These salinities were 21.0, 25.1, 29.4, 33.5, 37.5, 41.9, 50.2, 58.6, 67.0, 75.4, and 83.7‰. The effect of different salinities on the population growth in *R. heterocaryotica* is shown in text-figure 3. Laboratory populations increased at salinities as low as 26.8‰; moreover, the rate of population growth at initial salinities between 26.8 and 30.2‰ was greater than at salinities of 33.5‰. Salinities lower than 23.5‰ and higher than 37‰, on the other hand, appeared to inhibit reproduction, for the laboratory populations beyond these salinities did not increase. Curves showing the effect of initial salinities higher than 33.5‰ upon culture growth are not given because of the almost complete lack of growth of the cultures at these higher salinities.

DISCUSSION

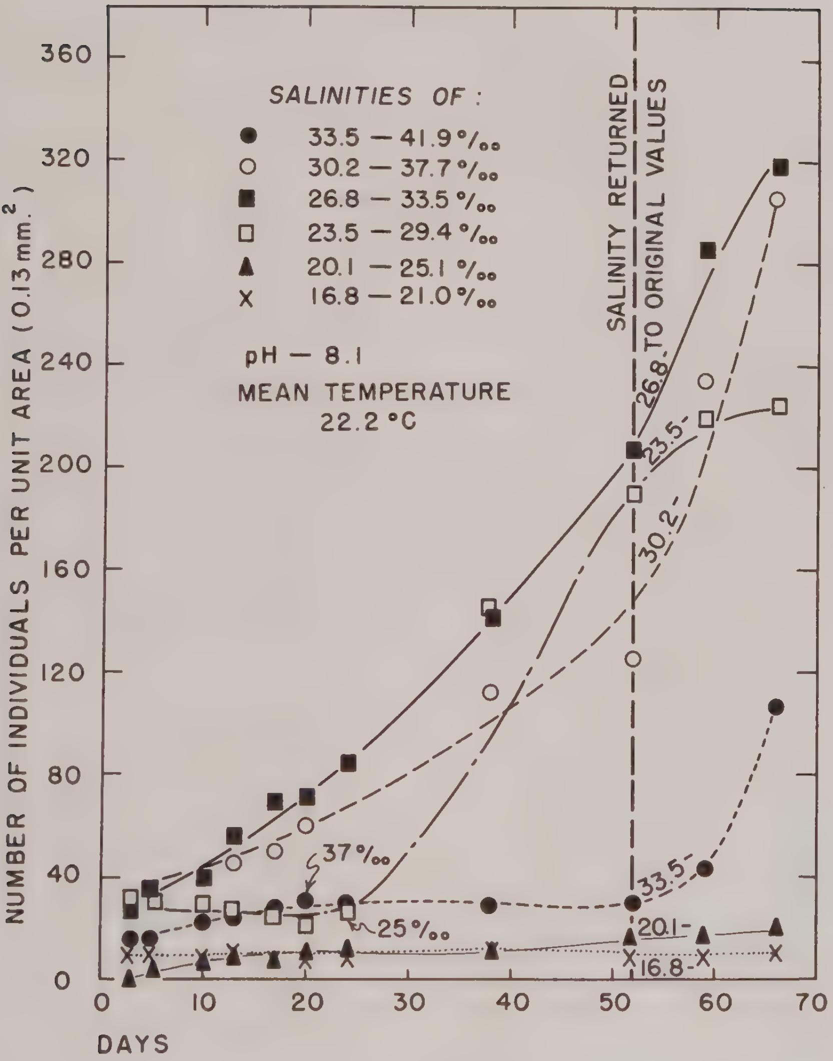
General statement: Marine conditions, even those of the smallest tide pool, cannot be reproduced within the confines of a laboratory culture dish. Certain "model effects" undoubtedly are caused by such factors as space restrictions and steadily increasing metabolites. More or less regular flushing and renewal of the water occurs in nature, but this is very difficult to acomplish in cultures. In a tide pool there are many diverse organisms, each having a particular part to play in the economy of that environment. Such a community may be said to be "dynamically balanced." In the laboratory only a part of such a system can be established, with the foraminifera and perhaps a few small protozoans, bacteria, and other unidentified forms. When a dynamic balance finally is achieved in such a culture, it will not be the same as that in the tide pool and probably will be found to contain different proportions of only a few elements of the natural environment.

Since a complex tide pool probably cannot be reproduced in the laboratory, the alternative may be to work with one environmental factor at a time, determine its effect on the population, and only later study combined factors. Complete duplication of nature may not be necessary for our purposes, since it may be only a few factors, such as temperature, food supply, or salinity, which set the limiting conditions for an animal in a particular environment.

The relative change or stability of population size in a species is considered to be a good indication of its response to any ecologic factor, reflecting the range of conditions required for the success or failure at all growth stages of an organism. In a young culture under favorable environmental conditions the number of individuals at successive time intervals will show a characteristic form known as the logistic growth curve (Allee *et al.*, 1949, p. 301). The growth form of a population may be divided into at least six regions.

These are: (1) the initial reaction of the population to its environment; (2) the period of increasing growth rate; (3) the period of decreasing growth rate; (4) the plateau or equilibrium position about which the population may fluctuate for an indefinite time; (5) period of decline because of adverse environmental factors; and (6) extinction: the death of the population. In the behavior of the cultures described above, these periods were found to vary in duration and size depending upon the species and the conditions in the culture. Thus, for any single species it will be environmental factors which determine the shape of the curve. Under adverse reproductive conditions, as shown, for example, by the 16.8‰ salinity curve in text-figure 3, there appears to be little, if any, population growth. With more favorable environmental conditions, as in the 26.8–30.2‰ salinity cultures, the population curve rises sharply and if continued presumably would reach the plateau position.

Food requirements: Foraminifera have been reported to feed upon a wide variety of particulate food. While this appears to be true for species such as *Rotaliella heterocaryotica*, it does not seem to be true for others such as *Rotaliella* sp. (see text-figure 1). Many forms may have specialized food requirements and may be found to ingest only certain materials, such as particular species of diatoms. The fact that a foraminifer under culture conditions will eat only a certain food, however, does not necessarily mean that this is its principal food under natural conditions. Some foods may be more efficiently captured and metabolized than



TEXT-FIGURE 3

Growth of laboratory populations of *Rotaliella heterocaryotica* Grell at different salinities.

others, and some may contain toxic elements. The nutritional role of bacteria is unknown.

The concentration of food material is important. Too much may be as bad as or even worse than too little. A suggestion of this may be seen in text-figure 1, in which the initial rate of growth of *Rotaliella heterocaryotica* when fed one unit concentration is greater than that when fed twice as much. The lower initial rate of growth in the population fed two units of food may be caused by the "antagonism" of a large population of bacteria attacking the uneaten food cells. On the other hand, when the size of the population enables it to utilize the available cells more fully, the growth curve in this population gradually becomes similar to the population given less food. The extra supply of food, however, allows the culture to maintain a higher population level.

Similar results have been observed in cultures in which living algae have been used as food material, but the amount of algae present is difficult to assess with accuracy. Excessive concentrations of living diatoms and/or green flagellates have been observed to have depressive effects on the foraminiferal populations. This has also been noted by Arnold (1954*b*, p. 411), who attributes the phenomenon partly to certain chemical effects associated with excessive algal growth, and partly to a form of algal choking.

Temperature results: There appear to be at least five critical temperatures of interest. These include (adapted from Orton, 1920, p. 360):

1. Lowest temperature for survival;
2. Lowest temperature for successful reproduction;
3. Optimum temperature for successful reproduction;
4. Maximum temperature for successful reproduction;
5. Maximum temperature for survival.

The two mean temperatures of 14.5° C. and 22.2° C. used in the experimental studies of *Rotaliella heterocaryotica* appear to lie within the reproductive temperature-range of this species. This was shown experimentally by the population growth at each indicated temperature. Further experiments may define the reproductive limits of this species more accurately. The maximum temperature of 26.0° C., endured for limited periods, was apparently within the survival temperature-range of the species, and may also have been within the reproductive range. Since this maximum temperature was maintained for only a short time, nothing is known of the effect of a longer exposure.

Salinity results: The lack of growth at salinities of 16.8–20.1‰ is not surprising in view of what is known of the ecology of other foraminifera. Such a lowered salinity may be one of the major factors in preventing the colonization of brackish-water environments by species adapted to open-ocean environments. The sudden growth, after the twenty-fourth day, of the culture started at a salinity of 23.5‰ may be explained by an increase in salinity due to evaporation from the culture dish. During the first fifty-two days of the experiment, the salinity increased from 23.5‰ to 29.4‰. Interpolation between these two values indicates that a salinity of approximately 25‰ was presumably reached on the twenty-fourth day. After this time, presumably because of favorable salinities, a rapid increase in the population occurred.

The apparent lack of growth, after the twentieth day, of the culture started at 33.5‰ salinity can be explained similarly. Here the population, which at the beginning of the experiment was increasing normally, gradually decreased its productivity as the salinity rose above the critical value. The critical salinity, as determined by interpolation, appears to have been approximately 37‰.

It is curious to find such results in a species originally from the Adriatic Sea, where relatively high salinities obtain. This suggests that *Rotaliella heterocaryotica* may have been living near its upper salinity limit for successful reproduction. Another possibility is that the immediate environment where the species was collected may have been influenced by fresh-water runoff, and the species therefore rarely experienced such high salinities.

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Scripps in the Present Tense[1]

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EXCEPT FOR A SPRINKLE of islands, 5,000 miles of empty ocean lie between the Roaring Forties and the beaches of southern California. Waves born in the angry winter of the Southern Hemisphere cross this expanse in six to eight days. They travel with gradually diminishing force and gradually growing speed through the waters where winter is never known and into the Northern Hemisphere as it lies with its face to the sun. They arrive off southern California as low,. regular swell. One strikes a ridge offshore, rises steeply, and bears landward on its flank a teetering surfrider. Others break just at the beach, rearing up head-high. There is a moment when the thin, transparent crest spills smoothly downward just before the whole mass crashes into a dazzle of blue-white surf.

We know that such waves arrive from the Southern Hemisphere because several years ago scientists from the University of California's Scripps Institution of Oceanography conducted research on such waves. By studying weather maps, they determined that waves of a specific direction, height, and period could only have originated in the Southern Hemisphere.

In its half-century of existence, the Scripps Institution has become a storehouse of information on the Pacific. The sheer size of this ocean is a little hard to realize. The 5,000 miles between the storm and the last expression of its energy is but one of the giant dimensions of the Pacific. It occupies almost half the surface of the globe. If all the continents were made into one, the resultant land mass would not entirely fill the Pacific Basin. The planet Mars, visible in some detail to our telescopes from 35 million miles away, is much smaller in area. The Pacific Ocean is the biggest thing on earth.

Much of what is known of this great entity has come from Scripps' researches. The Institution has been growing rapidly during the past decade and the accumulation of knowledge has increased.

This article will be chiefly concerned with what people are talking about at Scripps at present, the zestful shoptalk of men who work close to the very limits of knowledge, but first a few paragraphs on the Institution might be useful:

Scripps began as a marine station in the early 1900's. It bears the name of two of its founders, the brilliant publisher E. W. Scripps (of the Scripps-Howard newspaper chain) and his half-sister, Ellen Browning Scripps. The Institution has been a part of the University since 1912. It is located at the northern edge of La Jolla, a pretty and quiet southern California town. Behind the shore-

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[1] Contribution from the Scripps Institution of Oceanography, No. 807. The author is Manager, Office of Oceanographic Publications, Scripps Institution of Oceanography.

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from Bulletin of the International Oceanographic
Foundation, vol.1, no.3, 1955. pp.30-38.

THE UNIVERSITY *of California's Scripps Institution of Oceanography, La Jolla, Cal.*

side campus, abrupt slopes lead to a mesa covered with eucalyptus. The University owns 177 acres here, only a fraction of which is in use at present. Adjacent to the University land a group comprised principally of Scripps staff members has developed an attractive cooperative subdivision.

The Institution's mission is twofold: research and teaching. It is a graduate school, offering work leading to the M.S. and Ph.D. The oldest oceanographic institution in the country, and for many years the only one affiliated with a university, it not unsurprisingly leads all others in the number of degrees earned. Its students hold many outstanding positions in the field of oceanography. During the past few years, enrollment has averaged around 50 students a semester.

Associated with the Institution are two fisheries laboratories, the South Pacific Fishery Investigations of the U. S. Fish and Wildlife Service and the Inter-American Tropical Tuna Commission.

The campus is also headquarters of another University activity, the statewide Institute of Marine Resources, whose purpose it is to foster research and education in the development of fisheries and other resources of the sea.

Research fleet

Scripps operates the largest oceanographic research fleet in the world. This is scarcely an Armada, of course. But the five busy ships have sailed a total of approximately 400,000 miles in the past five years. Almost every month in the year at least two of them have made survey cruises over part of a pattern that extends from the Oregon border to the tip of Baja California. These cruises have been undertaken on behalf of the California Cooperative Oceanic Fisheries Investigations, a continuing study of the state's pelagic fisheries, particularly the sardine. These voyages account for about two-thirds of the miles sailed. The others have been accumulated in the course of the In-

THE Spencer F. Baird, 143-*foot former tug, is one of the five ocean-going research vessels operated by the University of California's Scripps Institution of Oceanography.*

Newest addition *to Scripps' fleet is the* Stranger, *a yacht which was recently given to the University. She is being refitted for research.*

stitution's eight long expeditions in the Pacific. The longest of these was Capricorn, which took the *Spencer F. Baird* and *Horizon* to the fabled South Seas. Other voyages have reached Alaska, Japan, the Marshalls, Peru. Planned for the fall of 1955 is Eastropic, in the course of which Scripps scientists will again visit the northern coast of South America. These cruises have received support from the Navy.

Research staff

The research staff of the Institution numbers around 100. Non-academic employees in a variety of jobs bring the payroll to approximately 500 persons.

The research program of the Institution embraces many aspects of the sea. It can be separated into four formal divisions, but individual projects often cross these boundaries. The chief topics treated are geophysics, chemistry, geology, and biology.

Like a healthy individual, a thriving institution is less preoccupied with its past or worried over its future than engrossed in the present. New data and new concepts appear unceasingly. Here are some of the things that Scripps people are talking about today:

Edge Waves. In 1846, Sir George Stokes mathematically defined what he called "edge waves." It has thus been over a century before they could be found in nature. Walter Munk recently identified them as a source of some of the "noise" that has given him trouble on his tsunami recorder. Before leaving for Europe on his sabbatical, he completed a paper (with Frank Snodgrass and George Carrier)

ABOUT THE SIZE *of a pumpkin seed, the euphausiid forms a major item in the diet of the largest creature on earth, the whale. Scientist Betty Boden has recently extracted a new photosensitive pigment from the eyes of the euphausiids, which are part of the plankton.*

on the phenomenon and submitted it to *Science*.

Light. Brian and Betty Boden have left for the Mediterranean after a short visit to Coconut Island, Hawaii, where they made light measurements. Mrs. Boden has recently published in *Nature* on the discovery of a new photosensitive pigment, euphausiopsin, in the eyes of euphausiids. Her husband's work on the euphausiids of the Pacific (done with Martin Johnson and Ed Brinton) is scheduled for publication by the University of California Press late this fall.

Heat Flow. For several years now, a number of people among whom are Roger Revelle, Scripps' director, and Sir Edward Bullard of the National Physical Laboratory, Teddington, England, have been measuring heat flow through the ocean floor. About 25 measurements have been made in the Pacific. The warmest spot yet found lies on the Albatross Rise to the west of South America. A long paper summarizing the heat-flow work has been accepted as a Memoir of the Geological Society of America.

Flamingos. As zoo keepers long have known, you can brighten up your flamingos by feeding them ground-up shellfish in addition to their usual diet of grass pellets, millet, rice, and dried flies. Denis Fox is interested in the biochemistry of the process and has been studying flamingos at the San Diego zoo. Some of the red pigment, astaxanthin, eaten by the flamingo reaches the skin and feathers, but most of it is broken down in its passage through the bird's body. Fox reported on his work at the Biochemical Congress in Brussels this summer and has published in *Nature* on it.

Lateral Line. For several months last year physiologist Ted Walker engaged in a duel of wits with a small sea perch, *Cymatogaster aggregata* Gibbons. For quite a long time, *Cymatogaster* won every round. Walker is working on the lateral line of fishes. To study the response of the perch to pressure vibrations in the water he designed an experiment that was simple in principle, but, thanks to the sea perch's acuity, remarkably hard to carry out. Essentially, he hoped to train the fish to recognize that a pressure signal of a specific frequency would mean it would find food in a specific place. But first the fish watched the food being introduced into the tank through transparent glass tubes. Walker painted the tubes black. The fish then watched the oscillation of a pressure bubble in the manometer. That was masked. *Cymatogaster* possesses monocular vision, that is, his eyes can work independently. Walker was working with two dishes. The fish focused an eye on each dish. "I

THIS FISH *wears a bathing cap. Theodore Walker fashioned the latex cap in the course of his studies of the lateral-line system.*

felt at times that the fish should have kept the notebook," Walker said. At one point in the research, Walker fashioned latex "bathing caps" to decrease the sensitivity of the lateral line around the head. When the fish had apparently learned to respond as desired to the appropriate signals, Walker found it was actually cueing to the difference in vibration coming from the pressure-actuating motor rather than pressure itself. These behavioral studies have been combined with investigations of the structure of the lateral line system.

Underground Oceanography. Doak Cox came over from Hawaii last fall to spend some time working on "underground oceanography." Cox has been studying the movement of ocean water that seeps through the permeable Hawaiian rock to underlie the water table of fresh water. His data come from the wells which water the lush Hawaiian plantations.

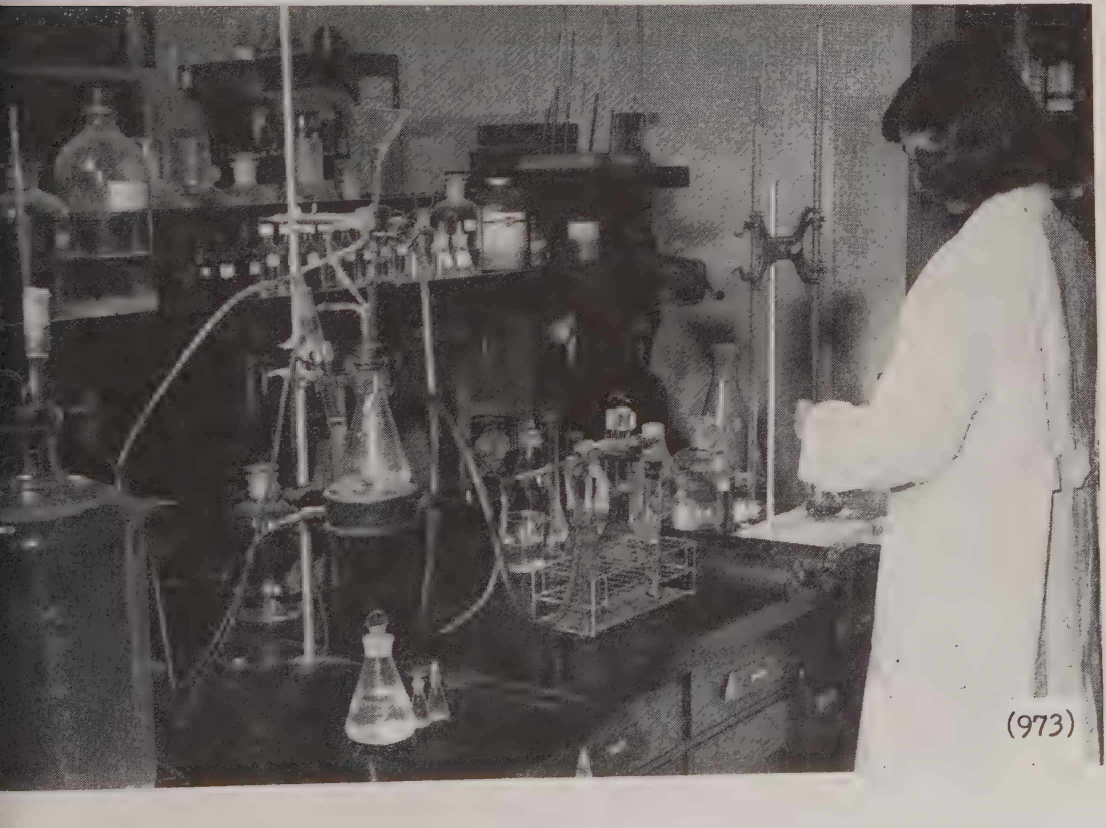
Oceanic Fronts. The ocean has well-defined boundary zones between cool and warm water which by analogy with meteorological practice Townsend Cromwell has called "fronts," a word that meteorologists, by the way, again from analogy adopted from the alien science of warfare. Cromwell and Joe Reid have submitted a paper to *Tellus* dealing with two such clearly marked boundary zones in the tropical Pacific.

WILLARD N. BASCOM, *research engineer, aboard the* Spencer F. Baird *on Capricorn Expedition of the University of California's Scripps Institution of Oceanography, caught by a sudden breaking wave.*

Sewage. What to do with sewage is one topic under frequent discussion. California is paying the penalty for its explosive growth during the past decade. One of the many problems presented by its enormous new population is that of sewage and the cities are turning to Scripps for advice. That is particularly true of San Diego, a municipality whose bay is already seriously contaminated. The prescription of the engineers has been a sewage treatment plant whose cost is estimated between 16 and 30 million dollars. Scripps staff members have been called upon for advice and it is possible that the Institute of Marine Resources will establish a long-term project dealing with the subject.

Detergents. Carl Oppenheimer, who spent the spring in Norway—his second visit there—has found that one part per million of some common household detergents is lethal to marine perches in laboratory aquaria. The substance does not poison the fish, but so affects the gills that the creature suffocates. Whether the stuff is as deadly in nature as in the laboratory remains to be determined.

Middens. Indefatigable Carl Hubbs has received support from the National Science Foundation for one of his projects, the determination of climatic conditions along the Pacific coast in the past. For evidence, Hubbs depends upon kitchen middens, prehistoric rubbish heaps in which have been found charcoal and shells. Charcoal (carbon 14) dates the heaps, the shells (oxygen 18) give the oceanic temperatures from which terrestrial climates can be to some degree extrapolated. Hubbs finds several periods in which the climate differed from that of today, with corresponding dif-



A VIEW *of one of the microbiology laboratories of the University of California's Scripps Institution of Oceanography.*

ferences in fauna and in the size of the human population. Today's bleakly barren Baja California coast has in the past supported thriving Indian populations, he finds. Hubbs' work with isotopes may be given further impetus with the prospective appointment of Hans Suess and Harmon Craig to the Institution's staff.

Diving. Scripps remains the only campus of the University at which the official use of self-contained underwater breathing apparatus is allowed. The Institute of Marine Resources' Acting Director Admiral Charles Wheelock, Conrad Limbaugh, and others have spent several months framing a policy for use of the equipment. Their work is being closely followed by other agencies which have found the gear valuable in research.

Sardines. The news on sardines, in the study of which Scripps has joined four other research groups, is that the 1954-55 season's catch, while puny by the standards of the flush 1930's, was about 20 times the size of that of the previous season. The sardines came back in 1954 to spawn widely off southern California and 67,000 tons were caught during the fall. Spawning has again been widespread in the same area during the spring of 1955, but comparative figures for the two years are not yet available.

Rockefeller Grant. Last year the Rockefeller Foundation gave the University a million dollars to support expanded research in marine biology at Scripps over a period of years. A La Jolla committee headed by Adriano Buzzati-Traverso, is planning the use of these funds. Scheduled for the spring of 1956 is an international symposium on marine biological research.

These few examples may illustrate the breadth of Scripps program. They also emphasize the essential continuity of Scripps' half century of study of the great Pacific.

Deep-Sea Research, 1955, Vol. 3, pp. 66 to 73. Pergamon Press Ltd., London.

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Occurrence of bacteria in pelagic sediments collected during the Mid-Pacific Expedition

Richard Y. Morita and Claude E. ZoBell

Abstract—Bacterial populations ranging from hundreds to thousands per gram wet weight were demonstrated in pelagic sediments (red clay and globigerina ooze) taken during the Mid-Pacific Expedition. The abundance of viable bacteria in these sediments decreased with core depth. Although certainly most important as geochemical and biological agents in surface sediments at the mud-water interface, living bacteria were found at the bottom of the longest cores examined, nearly 8 metres, representing material believed to have been deposited more than a million years ago. A few explanations are offered to account for the presence of bacteria in this material of great antiquity.

INTRODUCTION

In 1950 the Mid-Pacific Expedition afforded an opportunity to investigate the occurrence and kinds of bacteria in red clay and globigerina ooze. It was a joint expedition of the Scripps Institution of Oceanography and the U.S. Naval Electronics Laboratory, primarily for exploring the ocean floor between California and the Marshall Islands (see Fig. 1). Bottom profiles along the track, as indicated by echograms, have been reported by Dietz *et al.* (1954). Numerous cores were collected from water depths ranging from 1,700 to 6,000 metres.

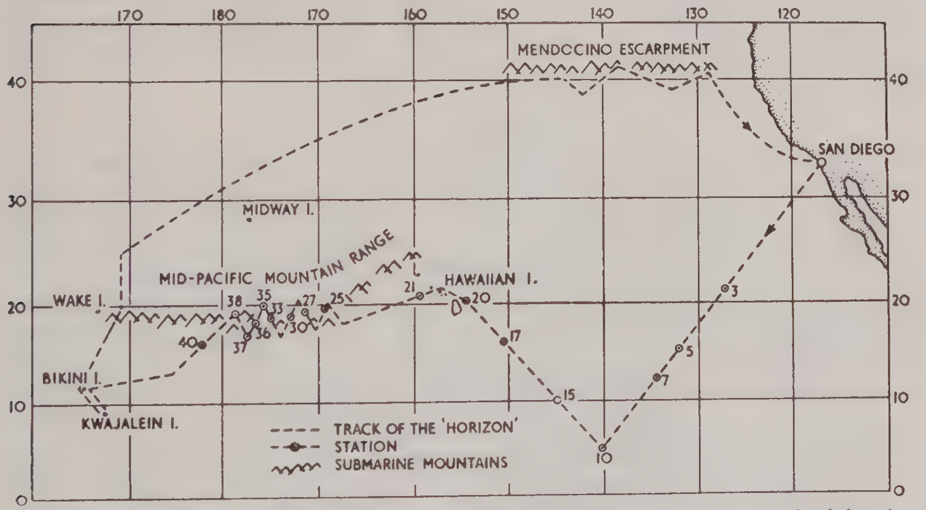
170
180
170
160
150
140
130
120
40
30
20
10
0
MENDOCINO ESCARPMENT
SAN DIEGO
MIDWAY I.
MID-PACIFIC MOUNTAIN RANGE
HAWAIIAN I.
WAKE I.
BIKINI I.
KWAJALEIN I.
38
35
33
27
25
21
20
40
37
36
30
17
15
10
7
5
3
TRACK OF THE 'HORIZON'
STATION
SUBMARINE MOUNTAINS

Fig. 1. Track of the Mid-Pacific Expedition. The R/V *Horizon* was accompained by the EPC(R) 857 to Bikini Island.

Prior to 1950 little was known regarding life in pelagic sediments, although there is ample evidence for an abundant and physiologically versatile microflora in near-shore sediments collected from many different parts of the world (ZoBell, 1946a). In the absence of field data some authors have tacitly assumed that, owing to inadequate organic nutrients, high hydrostatic pressures at great depths, and other adverse environmental conditions, pelagic sediments are mostly devoid of life. FISCHER (1894) noted the growth of only one or two bacterial colonies on plates of sea-water gelatin medium inoculated with one-gram samples of sediment taken from depths of 1523 and 2406 metres in the Gulf of Mexico, and he was not certain whether these were contaminants. WAKSMAN (1934) declared that true oceanic bottom deposits in the Atlantic contain few bacteria, but he gave no data to substantiate this conclusion.

In Pacific Ocean sediments of terrigenous origin, RITTENBERG (1940) found 10^4 to 10^6 bacteria per gram as compared with a maximum of 10^3 bacteria in the only pelagic sediment sample collected ; this from a water depth of 3005 metres. That hydrostatic pressure is not a deterrent to bacterial life at great depths was demonstrated by ZOBELL (1952) and MORITA (1954), who found millions of viable bacteria per gram of sediments taken from depths exceeding 10,000 metres on the Danish *Galathea* Deep-Sea Expedition.

METHODS

Cores of bottom sediment were taken on the R/V *Horizon* with either a Phleger sampler or a modified Kullenberg piston-type corer. Immediately after being hoisted aboard the ship, the sediment was extruded and the core length measured. Strata representing different core depths were removed for bacterial analysis. Radially central portions of these core strata were dissected out with sterile instruments and transferred to wide-mouth bottles. In order to minimize the possibility of extraneous contamination, the freshly cut core strata ends were scraped clean two or three successive times with sterile instruments prior to taking the radially central sub-samples. These sub-samples were stored in the ship's refrigerator until they could be examined for the presence of bacteria ; generally within an hour or two after the sample was taken.

The relative abundance of different kinds of bacteria in the sediment samples was estimated by the minimum dilution method. Several different kinds of nutrient media were employed, since no one medium can provide for the growth of all kinds of bacteria. Medium 2216E for the general aerobic population had the following composition :

Sea water	1000·0 ml
Bacto-peptone	5·0 gm
Ferric phosphate	0·1 gm
Yeast extract	1·0 gm

Medium 2216E fortified with KNO_3 (1·0 gm/L), soluble starch (2·0 gm/L) or gelatin (120 gm/L) was used to demonstrate the presence of nitrate-reducing bacteria, starch hydrolysers and gelatin liquefiers respectively. The general anaerobic bacterial population was estimated in medium 2216E treated with sodium formaldehydesulphoxylate (1·0 gm/L) to lower the redox potential, and resazurin (0·001 gm/L) to serve as an indicator of anaeroboisis. Sulphate-reducing bacteria were demonstrated in medium M 10 E :

Potassium phosphate dibasic	0·2 gm
Magnesium suphate hydrated	0·2 gm
Sodium sulphite	0·1 gm
Ferrous ammonium sulphate	0·1 gm
Calcium lactate	3·5 gm
Ascorbic acid	0·1 gm
Bacto-peptone	1·0 gm
Yeast extract	1·0 gm
Bacto-agar	3·0 gm
Sea water	1000·0 ml

All media were adjusted to pH 7·5 and sterilized by heating in a pressure cooker to 121 C for 30 minutes in ½ oz. bottles fitted with plastic screw-caps. These receptacles can be manipulated and stored on a ship at sea more conveniently than the more conventional cotton-wool stoppered test tubes commonly used by land-locked bacteriologists.

In each series the first bottle, containing 9·0 ml of sterile medium, was inoculated with 1·0 gram of wet sediment. It follows that if bacterial growth occurs in such bottles and not in uninoculated controls, there must be at least one viable cell per gram of sediment. The bacteria in the sediment were diluted to extinction by powers of 10 to estimate the order of magnitude of the bacterial population. The dilution procedure consisted of mixing, by vigorous shaking, 1·0 gm of sediment with 9·0 ml of medium and then transferring, with an automatic pipette, 1·0 ml of this 1 : 10 dilution to another 9·0 ml of sterile medium to give a 1 : 100 dilution. This operation was repeated seriatim until the sediment had been diluted 1 : 1,000,000. Assuming a random distribution of bacteria in the sediment, bacterial growth in the 1 : 10,000 and all lower dilutions but not in the 1 : 100,000 dilution, for example, would indicate the most probable number of bacteria in the sediment sample to be between 10,000 and 100,000 per gram or a bacterial titer of 4. The bacterial titer is defined as the logarithm of the reciprocal of the highest dilution showing growth or other evidence of physiological activity.

About 5 ml of air was left in the bottles of inoculated media prepared for aerobic bacteria. The bottles prepared for sulphate-reducing and other anaerobic bacteria were filled to capacity with sterile medium and the screw-caps were tightly seated to exclude air.

The inoculated media were incubated for 21 days or longer, unless there was earlier evidence of bacterial activity. Increasing turbidity was generally indicative of bacterial growth. In questionable cases, particularly lower dilutions in which the sediment itself caused considerable turbidity, it was necessary to prepare wet mounts for examination by phase microscope in order to prove the presence of living bacteria. The media were tested for the appearance of nitrite or the disappearance of nitrate as indicative of the activity of nitrate-reducing bacteria :

$$KN0_3 + 2H \rightarrow KN0_2 + H_20$$

Lugol's iodine was employed to test for starch, which is hydrolysed by certain bacteria. Gelatin liquefaction, indicative of the presence of active proteolytic bacteria, could be observed visually. The blackening of sulphate medium, caused by the formation of ferrous sulphide, was employed as a criterion of sulphate reduction :

$$S0_4^{--} + 10H \rightarrow H_2S + 4H_20$$

$$H_2S + FeS0_4 \rightarrow FeS + H_2S0_4$$

Uninoculated bottles of media served as controls on sterility ; several bottles were maintained for many months without growth or other evidence of bacterial activity. Absence of growth or other activity in the higher (extinction) dilutions served as controls on technique.

FIELD OBSERVATIONS

Table 1 summarizes some of the properties of cores collected for bacterial analysis. The order of magnitude of the most probable number of bacteria per gram of wet sediment from the topmost and bottommost portions of the cores is given in terms of bacterial titer, which ranged from 0 to 4. Bacteria ranging in abundance from 10 to 10,000 per gram wet weight of sediment were demonstrated in all topmost portions of cores (*i.e.* material from the mud-water interface) and in nearly all deeper strata, regardless of water depth or core length. The pelagic sediments have far fewer bacteria than nearshore sediments of higher organic content. The latter commonly contain from 10^5 to 10^7 bacteria per gram wet weight.

The apparent preponderance of aerobic bacteria over anaerobic ones (see Tables 2 and 3) in sediment samples from most core depths was somewhat surprising, since there is ostensibly little or no free oxygen below the mud-water interface. Further observations are required to explain this anomaly. A good many of the bacteria have proved to be facultative aerobes, which grow preferentially in the presence of free oxygen, but can grow slowly under anaerobic conditions when essential nutrients are present. It seems doubtful, however, that the apparent preponderance of aerobes is always ascribable to technical difficulties in demonstrating anaerobes.

Is it possible that free oxygen is generated *in situ*, by the electrolysis of water or alpha-particle bombardment from radioactivity, for example, at a rate sufficient to provide for the oxygen requirements of aerobic bacteria ? Active aerobes consume oxygen at a rate of 10^{-13} to 10^{-12} mg/cell/hour (ZoBELL, 1940). At this rate of oxygen consumption an aerobic bacterial population of 10^4 per gram of sediment would require only from about 10^{-5} to 10^{-4} mg of free oxygen per ml per year – the equivalent

Table 1. *Bacterial titer of sediment at top and bottom of cores collected at different Mid-Pacific (MP) stations.*

Station number	*Location of Station*		*Water depth*	*Length of core*	*Type of sediment*	*Bacterial titer**	
	Latitude	*Longitude*				*Top*	*Bottom*
MP	*N*	*W*	*m*	*cm*			
3–1	20°51′	127°09·9′	4390	747	Red clay	3	0
5–3	14°22·1′	133°06·8′	5300	40	Red clay	4	2
7–2	12°47·5′	134°26·4′	4758	106	Globigerina ooze	1	1
10–2	4°37·2′	140°00·3′	4365	89	Globigerina ooze	1	1
15–1	10°43·5′	145°53·2′	4987	92	Volcanic ash	4	2
17–2	14°38·3′	151°58·4′	5942	122	Red clay	3	3
20–2	20°27·0′	154°55·1′	3825	96	Red clay	4	2
21–2	20°47·0′	159°59·0′	4484	145	Red clay	4	4
25–E	19°02′	169°44′	1759	77	Globigerina ooze	4	4
27–2	19°35′	171°50′	3750	88	Globigerina ooze	3	3
30–1	18°27′	173°14′	3709	71	Red clay	2	2
33–H	17°53′	174°27′	1707	55	Globigerina ooze	2	1
33–L	17°51′	174°17′	1720	43	Globigerina ooze	4	1
35–1	19°21′	174°58′	4841	75	Red clay	4	4
35–2	19°02′	174°58′	3935	363	Red clay	3	3
36–1	16°48′	176°27′	5032	319	Globigerina ooze	4	3
37–1	17°06′	177°18′	5032	275	Globigerina ooze	4	2
38–1	19°02′	177°18′	4712	366	Red clay	3	0
40–1	15°35·	177°30′	4121	387	Red clay	3	0

* 0 = No viable bacteria demonstrated in 1·0 gram of wet sediment.
1 = At least 10 but < 100 viable bacteria per gram of wet sediment.
2 = At least 100 but < 1,000 viable bacteria per gram of wet sediment.
3 = At least 1,000 but < 10,000 viable bacteria per gram of wet sediment.
4 = At least 10,000 but < 100,000 viable bacteria per gram of wet sediment.

of about 0·1 to 1·0 ppm per year. Possibly oxygen diffuses into bottom deposits rapidly enough to provide this much ; significantly the red clays and globigerina ooze samples are oxidizing in character.

Redox potential determinations on 236 samples from 19 cores of pelagic area sediments collected on the Mid-Pacific Expedition indicated that the red clay as well as the globigerina ooze at all core depths was in an oxidizing state. This is in direct contrast with nearshore sediments of high organic content in which reducing conditions (Eh = — 50 to — 350 mv) commonly prevail (ZOBELL, 1946b ; EMERY and RITTENBERG, 1952 ; MORITA, 1954).

Table 2. Titer of aerobic bacteria (first number in each column) followed by titer of anaerobic bacteria demonstrated in different strata of red clay cores collected at different Mid-Pacific Expedition stations.*

Core strata (centimetres)	*MP* 3–1	*MP* 5–3	*MP* 17–2	*MP* 20–2	*MP* 21–2	*MP* 30–2	*MP* 35–1	*MP* 35–2	*MP* 38–1	*MP* 40–1
0 to 10	3, 2	1, 1	3, 2	4, 2	4, 2	2, 2	4, 3	3, 2	3, 3	3, 0
11 to 50		2, 0		4, 1			1, 2			
51 to 100			3, 3	3, 2	4, 2	2, 1	4, 2			
101 to 200			3, 3	2, 1	4, 0					
201 to 400								1, 1	2, 0	0,0
400 to 750								3, 0	0, 0	0,0

Table 3. Titer of aerobic bacteria (first number in each column) followed by titer of anaerobic bacteria demonstrated in different strata of globigerina ooze cores collected at different Mid-Pacific Expedition stations.*

Core strata (centimeters)	*MP* 7–2	*MP* 10–2	*MP* 25–1	*MP* 27–2	*MP* 33–H	*MP* 33–L	*MP* 36–1	*MP* 37–1
0 to 10	1, 0	1, 0	4, 1	3, 2	2, 1	1, 1	4, 4	3, 4
11 to 50			1, 1	2, 0		1, 4		
51 to 100	2, 2	1, 0	4, 2	3, 0	1, 1			
100 to 200	1, 0							2, 3
200 to 400							4, 4	1, 2

* = No viable bacteria demonstrated in 1·0 gram of wet sediment.
1 = At least 10 but < 100 viable bacteria per gram of wet sediment.
2 = At least 100 but < 1,000 viable bacteria per gram of wet sediment.
3 = At least 1,000 but < 10,000 viable bacteria per gram of wet sediment.
4 = At least 10,000 but < 100,000 viable bacteria per gram of wet sediment.

Measurements made with a Beckman Model G meter, connected with bright platinum, glass and KC1-calomel electrodes inserted in the sediment samples, by the methods outlined by ZOBELL (1946b), showed Eh values ranging from + 150 to

+ 450 mv and pH values ranging from 6·58 to 7·97 in red clay. The redox potential of globigerina ooze ranged from + 150 to + 350 with pH values ranging from 7·47 to 7·55. There was little variation with core depth in either Eh or pH. The pelagic area sediments were fairly well buffered but very poorly poised, as indicated by the drift in Eh values while the determinations were being made. The poor poise, drift, or low O/R capacity is attributed to the low content of readily oxidizing or reducing constituents. Although the oxidizing capacity was low, the pelagic sediments were definitely oxidizing in character. This may help to account for the preponderance of aerobes over anaerobic bacteria.

An appreciable percentage of the bacteria were able to utilize the oxygen in nitrate as indicated by nitrate reduction. In general there were more proteolytic (gelatin-digesting) than saccharolytic (starch-hydrolysing) bacteria. Sulphate-reducing bacteria were sparse in numbers and sporadic in occurrence. These are the only strict anaerobes demonstrated in the pelagic sediments.

Morphologically the bacterial flora in the pelagic sediments closely resembled those in sea water and terrestrial sediments. Rod-shaped forms were by far the most prevalent with lesser numbers of vibrio, spirilla, and cocci. It is estimated that more than 90 per cent of the bacteria were short gram-negative rods ranging in length from 2 to 5 microns. Quite frequently elongated filamentous forms were observed in wet mounts. Very few spore-formers were detected. Yeasts were not observed, but mould fungi were fairly common, particularly in the topmost layers of pelagic sediment. Rather than being aerial contaminants, the moulds are believed to arise from spores that have settled to the sea floor.

DISCUSSION

The general occurrence of bacteria in all samples of recent pelagic sediments is noteworthy, this being the first evidence of an indigenous microflora in red clays and globigerina oozes. Finding no bacteria in some of the older material (MP3-1, core depth 747 cm ; MP38-1, core depth 386 cm, and MP40-1, core depth 387 cm) is equally significant, because in the first place negative results speak favourably for aseptic sampling technique, and secondly indicate that we have reached the lower limits of the biosphere.

Incidentally, we are convinced, from years of experience and numerous checks and controls on sampling and analytical technique, that the possibilities of contamination are negligible. The principal error is in the other direction, namely getting results that are too low rather than too high. This is because no one nutrient medium or combination of cultural conditions required for a highly diverse microflora can provide optimal conditions for the growth of all species or strains of bacteria. The direct microscopic examination of recently collected material constitutes further evidence that bacteria are present in pelagic sediments, but unfortunately this technique offers no clues concerning the viability of the cells.

Unquestionably bacteria are present at a minimum abundance reported in Table 1, 2, and 3, and they are viable as indicated by their growth in nutrient media. Less certain is the actual state and geochemical importance of bacteria in the pelagic sediments. Those in recent sediments in the vicinity of the mud-water interface are believed to be playing an important part in the mineralization of organic matter, in consuming free oxygen; in providing particulate matter (bacterial cell substance) as food for the associated bottom fauna, etc. ; but to what depth and in what age of sediments do these bacterial activities continue ?

According to ARRHENIUS (1952), red clays are deposited in the Pacific Ocean at an average rate of 2·3 mm per 1,000 years. At this rate some of the lower strata in cores MP3-1 and MP35-2, in which a minimum of 10^3 bacteria per gram were found, were deposited more than a million years ago. Have bacteria been acting on the material in these deposits for more than a million years, or are the bacteria in a state of suspended animation ? All available evidence points to a slow continuous activity of the bacteria.

Bacteria are more abundant, and there are more varieties, in the topmost layers of recently deposited sediment than in older sediments at greater depths. There is also a gradual decrease with depth (age) in the organic carbon content of pelagic sediments. Although the organic content of pelagic sediment is only 1 per cent. or less (REVELLE, 1944), the low concentration would not preclude the possibility of bacterial activity. Marine bacteria continue to be active in very dilute nutrient solutions, as has been pointed out by WAKSMAN and CAREY (1935) and by ZOBELL and GRANT (1943). The latter demonstrated bacterial multiplication and respiration after the organic content was reduced to 0·1 mg per litre (0·0001 per cent.).

Prolonging the period that bacteria could persist on low concentrations of organic matter is their ability to recycle carbon compounds until completely oxidized to carbon dioxide. Heterotrophic bacteria generally convert from 30 to 40 per cent. of the carbon of organic compounds into bacterial cell substance, the remainder being oxidized as a source of energy to carbon dioxide. Upon the death of the bacteria their protoplasm may provide carbon and energy for the growth of other bacteria.

Organic synthesis by autotrophic bacteria is another mechanism that may contribute to bacterial life in older sediments. Most of the sulphate-reducing bacteria found in marine sediments can utilize molecular hydrogen as a sole source of energy for the synthesis of protoplasm from the reduction of carbon dioxide or bicarbonate (SISLER and ZOBELL, 1954). If one could postulate or prove (e.g., through electrolysis, radioactivity, reaction of water on iron, etc.) the production of the essential hydrogen, autotrophic bacteria might merit much more attention by those who are concerned with a study of the lower limits of the biosphere or with the importance of bacteria as geochemical agents.

Acknowledgements—Special thanks are due to Dr. Roger REVELLE, scientific leader of the Expedition, J. D. FRAUTSCHY, R. F. DILL, L. GARRISON and G. E. BRAYTON, through whose co-operation the cores were made available for bacteriological analysis. The authors are also indebted to other members of the Expedition and to R. M. CASSIDY, N. FOUNTAIN, M. KNIGHT and A. D. WEBSTER for assistance in preparing apparatus and material for work at sea.

Contribution from the Scripps Institution of Oceanography, University of California, La Jolla, California, U.S.A., New Series No. 808. This paper represents results of research carried out by the University of California under contract with the Office of Naval Research.

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Printed in Great Britain by The Salisbury Press Ltd., Publicity House, Wilton Road, Salisbury, Wilts. (93308)

Transactions, American Geophysical Union Volume 36, Number 6 December 1955

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NUMERICAL FILTERS FOR DISCRIMINATION AGAINST TIDAL PERIODICITIES

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(Contribution from the Scripps Institution of Oceanography, New Series, No. 809.)

Abstract--Tidal contributions to a sea-level record can be reduced by a large factor by taking special weighted averages of hourly values. In the residual record it is possible to recognize changes of as little as a few millimeters taking place in a few days. The method might be useful in other geophysical problems.

Introduction--Tides often present troublesome 'high-frequency noise' in the study of longer-period fluctuations of sea level or other geophysical phenomena. Two methods are generally used to combat this trouble: (1) subtracting the predicted tide, and (2) taking averages. The latter method, which is the one herein discussed, is found to have the following advantages: (1) a greater degree of tidal elimination can be achieved than by subtracting the tidal prediction based on standard methods, (2) the procedure is independent of geographical location, and (3) it is not limited to locations where the tidal constants are known. This method has the disadvantage that it eliminates non-tidal oscillations of high frequency, and it is therefore unsuitable for studying variations with periods close to those of the tides. The computational difficulties are probably of the same order for both methods.

In this paper we shall consider only the elimination of the diurnal and shorter-period tides from data that are in the form of tabulated hourly (mean solar) values. The usual averaging processes are the 'straight' (in contrast to 'weighted') 24-hourly and 25-hourly averages, to be referred to as the A_{24} and A_{25} filters. DOODSON and WARBURG [1941] give a considerably more effective filter consisting of a 39-hourly weighted average, which they call 'multipliers for mean sea level.' This will be referred to as filter B_{39}. This filter was developed by combining a number of simple filters, each of which discriminates strongly against one or more of the principal tidal constituents. By approximately the same method we have developed a filter using a 51 hourly weighted average, to be designated as C_{51}. Neither the B_{39} nor the C_{51} filter was developed by a systematic method. The systematic development described below led to a series of filters, $D_{15}, D_{17}, \ldots, D_{51}$. After our extensive computational effort we are more than ever impressed with the effectiveness of Doodson's simple scheme.

Response characteristics of weighted averages--Let y(t) represent the input data consisting of signal plus noise, Y(t) the filter output. The averaging process is to be carried out according to

$$Y(t) = \sum_{i=-N}^{N} w_i\, y(t-i) \qquad w_i = w_{-i} \quad \ldots\ldots\ldots\ldots\ldots (1)$$

where 2N + 1 represents the number of values summed for the average, and w_i are the 'weight factors.' Y (t) can be called 'mean sea level' in accordance with common terminology in oceanic tidal work. The arguments of Y and y are integers representing numbers of mean solar hours. The weight factors are normalized according to

$$\sum_{i=-N}^{N} w_i = 1 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

in order to give unit response for a component of infinite period.

The process (Eq. 1) of converting y into Y is a convolution of discrete functions. It can be shown to be equivalent to multiplying every sinusoidal component of y by the filter response factor

$$F(n) = \sum_{i=-N}^{N} w_i \cos in \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

without changing its phase (see, for example, WOODWARD [1953]). The quantity n is the hourly speed and is equal to 2π divided by the period in hours.

According to (1) we are considering only averages carried out over an odd number of hourly values. This is not a serious restriction, as a relatively large number of hours must be taken into account in order to achieve a satisfactory filter. Of more importance is the restriction of taking a symmetrical weighting array with respect to past and future data. We thus retain only those filters that introduce no phase change in the sinusoidal components of y, and exclude a number of filters having otherwise desirable characteristics. Incidently, it is a general rule that only filters which take into account both past and future values have this property of no phase shift.

In the case of the filters A which have equal weight factors, F is given by the simpler expression

$$|F| = |M^{-1} \csc(n/2) \sin(Mn/2)| \qquad (4)$$

where M represents the number of consecutive hourly values of y taken into the average.

Criteria for determining an optimum filter--It will be convenient to define the autocorrelation function of any function f(t), t = 1, 2, ..., by the relation

$$\psi_f(\tau) = < \bar{f}(t)\, f(t - \tau) > \qquad (5)$$

where the symbol $< \ldots >$ denotes the time average

$$\lim_{T \to \infty} (1/2\,T) \sum_{t=-T}^{T} \ldots \qquad (6)$$

If two functions f(t) and g(t) are such that

$$\psi_{f+g}(\tau) = \psi_f(\tau) + \psi_g(\tau) \qquad (7)$$

f and g are said to be uncorrelated.

Let us consider the input signal y to be composed of two parts

$$y(t) = s(t) + u(t) \qquad (8)$$

s being the signal, and u the (unwanted) noise, which, for the time being, is not necessarily restricted to purely tidal noise. The corresponding quantities after filtering by (1) will be denoted by S and U, and it follows from the linear properties of transformation (1) that

$$Y(t) = S(t) + U(t) \qquad (9)$$

The problem now is to find the 'best' possible values of w_i. The procedure is to some extent arbitrary. LEVINSON [1947] for example discusses the separation of signal and noise by minimizing the quantity

$$< [\, Y(t) - s(t)\,]^2 >$$

with respect to each weight factor for weighted averages which consider only past data. In the particular case of the weighted average (1), Levinson's criterion leads to the relation

$$\sum_{i=1}^{N} w_i \left\{ \psi_y(k+i) - 2\psi_y(k) + \psi_y(k-i) \right\} + \psi_u(k) = 0 \qquad (10)$$

$$k = 1, 2, \ldots, N$$

provided that the noise is uncorrelated to the signal. Eq. (10) together with (2) determines the values of w_i.

The above method requires preknowledge of the autocorrelation of both the signal and the noise. It is difficult for us even to guess what the autocorrelation of the signal might be, and we shall therefore develop a somewhat different scheme which requires only that we prescribe the autocorrelation of the noise.

Whereas in Levinson's scheme the weight factors are determined by the criterion that the mean sea level Y resemble as closely as possible the input signal s, here we shall require that the output noise U be as small as possible, retaining, of course, the condition of unit response for zero frequency. We thus require that

$$< [\, U(t)\,]^2 > \; \equiv \; \psi_U(o) \; = \; \sum_{i=-N}^{N} \; \sum_{j=-N}^{N} \; w_i \, w_j \, \psi_u(i-j) \qquad \text{.........} \; (11)$$

be a minimum with respect to all the w_i. Instead of the Lagrangian multiplier technique, we shall employ the equivalent method of eliminating w_o by means of (2) and differentiating with respect to the remaining w_i. After some rearrangement this leads to

$$(1/4)\,(\partial/\partial w_k \; \psi_U)(o) \; = \; \psi_u(k) - \psi_u(o) + \sum_{i=1}^{N} w_i \Big\{ 2\psi_u(o) - 2\psi_u(i) - 2\psi_u(k)$$

$$+ \psi_u(k+i) + \psi_u(k-i) \Big\} \; = \; 0 \qquad \text{....................} \; (12)$$

$$k \; = \; 1, 2, \ldots, N$$

again provided that the noise is uncorrelated to the signal. Eq. (12) together with (2) determines the values of w_i. First, however, we must specify the function $\psi_u(\tau)$ for all τ from 0 to 2N, its values for negative argument being equal to those for the corresponding positive arguments because of symmetry.

The autocorrelation of the tide--Let us denote the purely tidal noise by $z(t)$. It is well known that the tide can be accurately represented by a finite series of the form

$$z(t) \; = \; \sum_j \; H_j \cos(n_j t + \epsilon_j) \qquad \text{....................} (13)$$

The semi-harmonic development of Darwin [SCHUREMAN, 1941] is adequate for our purpose as it can be shown that the variation of Darwin's 'constants' is slow enough to be unimportant.

Sinusoidal functions are uncorrelated according to (7) if they have periods which are different one from another and do not 'alias' together. The autocorrelation of the tide z is thus found to be

$$\psi_z(\tau) \; = (1/2) \; \sum_j \; H_j^2 \; \cos n_j \tau \qquad \text{....................} \; (14)$$

independent of the ϵ_j.

The only tidal elements that enter are the constituent amplitudes H_j and speeds n_j. The speeds have been precisely determined from astronomic observations and, being characteristic of each constituent, do not depend on geographic location. The amplitudes do depend on location, but fortunately the calculation for determining the weight factors is not critical with respect to these values.

Our calculations are based on these conditions: (1) the same emphasis is placed on the diurnal and semidiurnal tide as is given by the equilibrium theory, and (2) for each of these the amplitudes H_j are taken proportional to the values given by the equilibrium theory. It is an observed fact that marked deviations from the latter condition are rare.

The theoretical amplitudes are called 'constituent coefficients' and will be denoted by c_j. In accordance with the above remarks, H_j will be replaced by c_j in (14).

In addition there are 'shallow-water constituents,' which are not present in the equilibrium theory. These arise from the distortion inherent in nonlinear coupling between various constituents. Their relative amplitudes vary considerably from place to place. We have selected one constituent (centrally located periodwise) for each of the 3-diurnal, 4-diurnal, 6-diurnal and 8-diurnal species, and arbitrarily assigned them the amplitudes shown in Table 2. These are included in the computation of the autocorrelation of the tide according to (14).

Non-tidal noise--The autocorrelation of the high-frequency noise x is not as easy to prescribe, but it is not necessary to do so with great accuracy. A large part of x will consist of something which is uncorrelated from one hourly value to another, that is, random noise. This will arise from noise whose correlation time is less than an hour as well as from round-off in tabulating the values. With regard to the latter, it may be noted that the U. S. Coast and Geodetic Survey follows the practice of rounding off the hourly tidal heights to tenths of feet. Assuming that the errors from this

Table 1--Numerical filters for discrimination against tidal periodicities; the values shown except filters A, B, and C, have been determined by the minimization requirement (12);

Item	A_{24}	A_{25}	B_{39}	C_{51}	D_{15}	D^*_{15}	D_{17}	D_{19}	D_{21}	D_{23}	D^*_{23}	D_{25}	D_{27}	D_{29}
F_D	.0436	.0403	.00205	.000521	.0938	.0784	.0493	.0396	.0385	.0354	.0320	.0301	.0248	.0223
F_S	.0327	.0182	.000619	.000075	.0408	.0392	.0267	.0201	.0171	.0111	.0050	.00215	.00526	.00631
F_H	.0724	.0189	.00716	.0149	.779	.794	.277	.0169	.0206	.0220	.0385	.0134	.00171	.00486
F_R	.204	.200	.216	.163	1.36	5.53	2.62	.955	.377	.446	1.42	.511	.297	.237
F_2	.637	.610	.410	.355	.691	.683	.656	.638	.631	.617	.602	.592	.565	.552
KQ_1	-.0988	-.132	.0172	.0112	-.0654	-.0839	-.112	-.125	-.122	-.110	-.0960	-.0882	-.0661	-.0567
OO_1	-.0702	-.106	.00959	.00687	-.03	-.0462	-.08	-.09	-.10	-.083	-.0744	-.07	-.05	-.05
J_1	-.0377	-.0754	.00361	.00297	.01	-.0056	-.04	-.06	-.06	-.053	-.0494	-.05	-.04	-.03
K_1	-.00287	-.0426	.00015	.00016	.0544	.0363	-.0015	-.0221	-.0234	-.0225	-.0205	-.0199	-.0169	-.0154
S_1	.00000	-.0400	.00000	.00000	.06	.0395	.00	-.02	-.02	-.020	-.0182	-.02	-.02	-.01
P_1	.00287	-.0374	-.00013	-.00015	.0608	.0427	.0047	-.0163	-.0178	-.0174	-.0162	-.0157	-.0136	-.0124
M_1	.0347	-.0067	-.00029	-.00106	.10	.0800	.04	.02	.02	.012	.0110	.01	.01	.01
O_1	.0750	.0328	.00299	-.00001	.143	.126	.0846	.0605	.0565	.0515	.0464	.0429	.0345	.0311
Q_1	.117	.0743	.0104	.00395	.19	.172	.14	.10	.10	.092	.0842	.08	.07	.06
$2Q_1$	.162	.118	.0225	.0114	.226	.220	.177	.151	.145	.135	.125	.128	.100	.0923
KJ_2	.0206	.0588	.00355	-.00017	.0963	.102	.08	.0696	.0590	.0383	.0148	.0048	-.0211	-.0243
K_2	.00274	.0426	.00033	-.00001	.05	.0547	.04	.044	.04	.025	.0108	.005	-.012	-.014
S_2	.00000	.0400	.00000	.00000	.0424	.0476	.0449	.0403	.0348	.0227	.0100	.0044	-.0106	-.0128
L_2	-.00278	.0248	-.00107	-.00001	.00	.0084	.02	.019	.02	.010	.0052	.003	-.00382	-.005
M_2	-.0352	.0064	-.00058	-.00008	-.0380	-.0345	-.0183	-.00889	-.0069	-.00434	-.0019	-.0004	.00255	.0029
ν_2	-.0518	-.0102	.00130	-.00013	-.07	-.0696	-.04	-.032	-.04	-.018	-.0090	-.004	.007	.009
N_2	-.0545	-.0128	.00171	-.00013	-.0772	-.0748	-.0509	-.0354	-.0299	-.0204	-.0101	-.0051	.00729	.0095
μ_2	-.0713	-.0299	.00503	-.00014	-.10	-.107	-.08	-.0583	-.04	-.035	-.0183	-.009	.010	.013
$2N_2$	-.0739	-.0325	.00565	-.00006	-.113	-.112	-.0822	-.0618	-.0530	-.0372	-.0196	-.0111	.0103	.0145
M_3	.0354	-.00650	-.00909	.00312	1.18	1.14	.401	.00924	-.0316	-.0330	-.00399	-.0171	.00213	.00652
MS_4	-.0179	.0242	.00484	.00210	-.331	-.433	-.153	-.0186	.00313	.00983	-.0165	.00818	.00067	-.00174
$2MS_6$	-.0248	.0193	-.00361	-.000106	.182	.362	.169	.0125	-.0142	.000424	-.0280	.0160	.00302	-.00407
$2(MS)_8$	-.0201	.0265	-.00871	.0466	-.0849	-.474	-.0479	.0312	-.00391	-.00842	-.113	.0104	.00006	-.00282
i									VALUES OF w_i					
0		1/25	0	.032261	.25700	2.83272	.03628	-.03067	.14327	.02177	-.33726	-.15709	.01939	.09053
1		1/25	2/30	.035960	-.07287	-2.39448	.05204	.16228	.04063	-.00017	.07374	.03737	.03879	.04155
2		1/25	1/30	.035256	.04605	1.63989	.20557	.07198	-.04820	.06426	.24728	.19865	.06201	.00293
3		1/25	1/30	.036544	.32901	-.28444	-.05504	-.24712	.03424	.13701	.14321	.06263	.04875	.03760
4		1/25	2/30	.035556	-.17606	-.47744	-.42339	.07564	.09343	.01307	.00138	-.02159	.02349	.05276
5		1/25	0	.035360	-.07667	.70698	.47811	.33142	.06154	-.05324	-.30526	-.01674	.02600	.04803
6		1/25	1/30	.028350	-.42740	-1.06138	.62305	.04116	.03523	.05186	.30551	.00795	.04563	.04765
7		1/25	1/30	.028655	.74944	.95451	-1.31861	-.13933	.02881	.09211	-.11590	.12101	.05234	.02810
8		1/25	0	.023034			.92013	-.20854	.01044	.08861	.33525	.12065	.04949	.03104
9		1/25	2/30	.025733				.42785	-.02789	.02731	.11993	.00081	.04748	.04510
10		1/25	0	.028147					.20015	-.12570	-.58318	-.03555	.02161	.01729
11		1/25	1/30	.022330						.19398	.44667	-.08389	-.03576	.01120
12		1/25	1/30	.023839								.18724	-.03818	.01927
13			0	.017542									.14865	-.02009
14			1/30	.011113										.09232
15			0	.018324										
16			0	.016226										
17			1/30	.011218										
18			0	.019327										
19			1/30	.004512										
20				.003704										
21				.007513										
22				.004004										
23				.003808										
24				.007708										
25				.000104										

*See text under Example b.

Note: The weight factors are not given for filter A (the straight 24-hourly average), as this filter is not expressible in the form of (1). The signs given the values of F for filter A assume that the result Y is centrally located in time with respect to the hourly values of y going into the average. Thus for the average of the tidal heights for 0^h, 1^h, . . . , 23^h of any day, the result should be tagged with the time 11:30 of that day, and then there is 0 or 180° phase change, depending on whether F is positive or negative.

for the various tidal constituents are values of F, determined by (3); all the filters listed
those marked with an asterisk were affected by an error in the computations

D_{31}	D_{33}	D_{35}	D_{37}	D_{39}	D_{41}	D_{43}	D_{45}	D_{47}	D^*_{47}	D_{49}	D^*_{49}	D_{51}
.0166	.00671	.00184	.000900	.000791	.000749	.000706	.000648	.000492	.00032	.000338	.00072	.000196
.00549	.00257	.000991	.000645	.000510	.000406	.000299	.000130	.000107	.00039	.000320	.00014	.000535
.00561	.00348	.00170	.000563	.000638	.000101	.000113	.000542	.000717	.000791	.0000645	.00155	.000290
.348	.365	.250	.190	.173	.168	.166	.164	.163	.184	.160	.342	.157
.518	.454	.420	.408	.401	.394	.389	.374	.352	.322	.325	.363	.292
-.0354	.00179	.0186	.0219	.0216	.0204	.0187	.0156	.0106	.00544	.00455	.0138	-.00167
-.0308	-.00306	.010	.0125	.0125	.0119	.0110	.00935	.00663	.00400	.00327	.00867	-.000216
-.0229	-.006	.003	.00477	.00499	.00485	.00454	.00392	.00290	.00212	.00162	.00393	.000276
-.0115	-.00445	-.00109	-.000204	.000005	.000071	.000090	.000105	.000114	.00031	.000120	.00035	.000100
-.010	-.004	-.001	-.0004	-.0003	-.0002	-.0002	-.0002	-.0001	.00019	.0000	.00014	.0001
-.00947	-.00401	-.00140	-.000692	-.00050	-.000425	-.000390	-.000304	-.000198	.00007	-.000080	-.00005	.000039
.00362	.000	-.002	-.00196	-.00196	-.00188	-.00178	-.00155	-.00120	-.00088	-.000753	-.00150	-.000278
.0230	.00924	.00195	.000199	-.00020	-.000316	-.000352	-.000354	-.000335	-.00078	-.000302	-.00090	-.000251
.0462	.0218	.010	.00674	.00580	.00531	.00493	.00468	.00335	.00135	.00216	.00284	.000899
.0735	.0396	.0229	.0181	.0165	.0155	.0146	.0130	.0105	.00625	.00737	.0103	.00397
-.0191	-.00461	.00263	.00409	.00371	.00298	.00213	.000739	-.00107	-.00282	-.00268	-.00077	-.00340
-.0120	-.00490	-.001	.000196	.0005	.000422	.000345	.000177	-.000055	-.00015	-.000301	.00012	-.000443
-.0110	-.00475	-.00125	-.000175	.00010	.000160	.000157	.000108	.000025	.00010	-.000075	.00019	-.000151
-.0050	-.00292	-.00175	-.00120	-.00088	-.000652	-.000445	-.000139	.000247	.00077	.000593	.00030	.000747
.00245	.00107	.00012	-.000095	-.00013	-.000130	-.000104	-.000054	.000020	.00006	.000086	-.00002	.000123
.0086	.0061	.004	.0028	.0022	.0016	.00114	.000443	-.0005	-.00166	-.00132	-.00051	-.002
.00940	.00678	.00442	.00331	.00257	.00197	.00141	.000560	-.000558	-.00200	-.00160	-.00059	-.00280
.0150	.0130	.009	.0081	.00636	.00500	.00365	.00158	-.00120	-.00466	-.00384	-.00111	-.00539
.0159	.0139	.0108	.00878	.00706	.00556	.00410	.00179	-.00130	-.00513	-.00424	-.00118	-.00597
.00784	.00525	.00197	.000663	.000142	-.000067	-.000120	-.000849	-.000017	.000164	.000076	-.0000786	.000117
-.00285	-.000987	.000093	.000426	.000241	.000051	-.000055	-.000091	-.000113	.000107	.000053	-.000134	.000423
-.00307	.00616	.00264	-.000622	-.000608	.000071	.000220	-.000099	-.00225	-.00242	.000057	-.00485	.000244
.00516	.00180	-.00253	.000540	.000242	-.000262	.000099	.000107	-.000216	.000521	.000065	.000706	.000121
.051993	.013027	.026644	.030100	.038886	.042787	.041362	.040769	.037652	.015520	.028190	-.027162	.023536
.061224	.037486	.026490	.036541	.039841	.040786	.041679	.039603	.034481	.045823	.030186	.099553	.027414
.022855	.062433	.051520	.044666	.040608	.039555	.039291	.035814	.032411	.022755	.033391	-.005821	.032803
-.008481	.041186	.068462	.048736	.041798	.038492	.033845	.032582	.034996	.027330	.035201	.029091	.034288
.067421	.027309	.033652	.048757	.041088	.032601	.031103	.033046	.035201	.039402	.035995	.042217	.034641
.087935	.052325	.025259	.031005	.029856	.028959	.031447	.033440	.033906	.047461	.034855	.048764	.033906
.022052	.060187	.041219	.009335	.017699	.029270	.031585	.032094	.033083	.039091	.032016	.065219	.031362
.024957	.010624	.004126	.012602	.021051	.026898	.030264	.031136	.030107	.002454	.029509	-.049745	.028991
.019676	-.038896	-.013264	.026400	.029890	.026253	.026944	.028236	.027623	.032050	.027048	.048229	.026567
-.021096	-.005750	.034358	.031519	.030450	.028444	.024263	.023333	.025209	.044621	.024648	.075983	.025217
.043198	.079748	.056975	.035942	.028109	.025794	.024209	.021245	.020207	.015036	.023259	-.006696	.025598
.103587	.102948	.049572	.035349	.026092	.022105	.022689	.021414	.019444	.011146	.021351	.005582	.022881
.035507	.042240	.040295	.024997	.022278	.021280	.019478	.021096	.022747	.022029	.019180	.023957	.018215
-.049158	-.026388	.002091	.015786	.018238	.018437	.019303	.020583	.020627	.023688	.019239	.024858	.018386
-.073666	-.066388	-.023191	.005583	.013181	.016707	.019609	.018708	.017039	.018995	.019727	.031414	.020009
.137992	-.043347	-.013248	-.002771	.010042	.017243	.016634	.016224	.017994	.013922	.018127	-.011496	.017322
	.157770	.002548	.005701	.012323	.013231	.013783	.015884	.017186	.033705	.015673	.081466	.013720
		.099815	.023685	.012502	.009528	.012450	.014485	.013431	-.011128	.012749	-.073496	.011578
			.051119	.013719	.011453	.010587	.009846	.010109	.016954	.009347	.051460	.009899
				.031793	.013325	.008751	.006272	.005724	.015602	.007117	.015233	.009243
					.018246	.008410	.004893	.003352	.003736	.005619	.008377	.008012
						.012996	.005897	.004955	-.006000	.004336	-.005213	.006001
							.013785	.006936	-.001480	.005119	-.041332	.005829
								.014408	.035047	.008139	.090334	.005349
										.014073	-.034357	.005647
												.015353

Table 2--Table of cos (in), i = 1, 2, . . .

Item	KQ_1	OO_1	J_1	K_1	S_1	P_1	M_1	O_1	Q_1	$2Q_1$	KJ_2
n	16.6834764	16.1391017	15.5854433	15.0410686	15.0000000	14.9589314	14.4966939	13.9430356	13.3986609	12.8542862	30.6265120
T	21.578	22.306	23.098	23.934	24.000	24.066	24.833	25.819	26.868	28.006	11.755
c	.0032	.0163	.0297	.5305	.0500	.1755	.0317	.3771	.0730	.0097	.0064
$\frac{1}{2}c^2$	.0000	.0002	.0004	.1407	.0012	.0154	.0005	.0711	.0026	.0000	.0000
i											
1	.95791	.96059	.96323	.96574	.96593	.96611	.96816	.97054	.97278	.97494	.86050
2	.83516	.84547	.85563	.86531	.86603	.86674	.87468	.88388	.89261	.90101	.48094
3	.64212	.66370	.68511	.70559	.70711	.70862	.72549	.74513	.76384	.78192	-.03281
4	.39500	.42963	.46419	.49752	.50000	.50248	.53011	.56248	.59349	.62365	-.53739
5	.11464	.16167	.20916	.25536	.25882	.26227	.30099	.34669	.39084	.43412	-.89206
6	-.17538	-.11901	-.06128	-.00429	0	.00429	.05268	.11046	.16691	.22281	-.99785
7	-.45063	-.39031	-.32718	-.26365	-.25882	-.25398	-.19897	-.13227	-.06612	.00035	-.82525
8	-.68796	-.63085	-.56905	-.50496	-.50000	-.49502	-.43796	-.36722	-.29552	-.22213	-.42243
9	-.86734	-.82167	-.76905	-.71166	-.70711	-.70253	-.64905	-.58053	-.50886	-.43349	.09826
10	-.97372	-.94772	-.91251	-.86959	-.86603	-.86242	-.81882	-.75962	-.69450	-.62310	.59152
11	-.99812	-.99907	-.98886	-.96794	-.96593	-.96385	-.93645	-.89395	-.84231	-.78149	.91977
12	-.93848	-.97168	-.99249	-.99996	-1.00000	-.99996	-.99445	-.97560	-.94428	-.90071	.99140
13	-.79984	-.86770	-.92314	-.96347	-.96593	-.96830	-.98913	-.99975	-.99485	-.97478	.78645
14	-.59385	-.69532	-.78590	-.86096	-.86603	-.87100	-.92082	-.96500	-.99126	-1.00000	.36210
15	-.33788	-.46813	-.59086	-.69946	-.70711	-.71467	-.79388	-.87338	-.93371	-.97510	-.16329
16	-.05345	-.20405	-.35238	-.49004	-.50000	-.50990	-.61639	-.73030	-.82532	-.90131	-.64311
17	.23546	.07611	-.08797	-.24703	-.25882	-.27057	-.39965	-.54417	-.67202	-.78236	-.94352
18	.50457	.35027	.18289	.01290	0	-.01290	-.15747	-.32598	-.48212	-.62419	-.98069
19	.73119	.59683	.44030	.27194	.25882	.24565	.09475	-.08858	-.26598	-.43474	-.74426
20	.89625	.79634	.66535	.51236	.50000	.48754	.34094	.15404	-.03537	-.22349	-.30021
21	.98586	.93309	.84145	.71766	.70711	.69639	.56541	.38758	.19718	-.00105	.22762
22	.99247	.99629	.95569	.87381	.86603	.85803	.75387	.59829	.41899	.22145	.69193
23	.91552	.98096	.99964	.97005	.96593	.96153	.89434	.77373	.61798	.43286	.96321
24	.76150	.88831	.97008	.99985	1.00000	.99985	.97786	.90358	.78335	.62256	.96576
25	.54336	.72564	.86918	.96113	.96593	.97041	.99911	.98019	.90606	.78105	.69888
26	.27949	.50578	.70436	.85656	.86603	.87519	.95674	.99903	.97945	.90040	.23702
27	-.00792	.24605	.48775	.69329	.70711	.72066	.85345	.95901	.99953	.97463	-.29097
28	-.29466	-.03307	.23528	.48252	.50000	.51728	.69582	.86247	.96519	1.00000	-.73777
29		-.30958	-.03452	.23869	.25882	.27884	.49388	.71511	.87831		
30		-.56169	-.30175	-.02150	0	.02150	.26049	.52561	.74361		
31		-.76953	-.54682	-.28021	-.25882	-.23730	.01051	.30513	.56845		
32		-.91672	-.75166	-.51973	-.50000	-.48001	-.24013	.06667	.36232		
33		-.99165	-.90123	-.72363	-.70711	-.69019	-.47549	-.17571	.13648		
34		-.98842	-.98452	-.87795	-.86603	-.85359	-.68057	-.40774	-.09678		
35		-.90727	-.99541	-.97211	-.96593	-.95913	-.84230	-.61574	-.32479		
36		-.75462	-.93310	-.99967	-1.00000	-.99967	-.95041	-.78746	-.53512		
37		-.54249	-.80218	-.95872	-.96593	-.97245	-.99800	-.91278	-.71630		
38		-.28759	-.61226	-.85208	-.86603	-.87932	-.98204	-.98430	-.85850		
39		-.01004	-.37732	-.68706	-.70711	-.72660	-.90355	-.99783	-.95397		
40		.26831	-.11463	-.47496	-.50000	-.52462	-.76752	-.95255	-.99750		
41		.52552	.15649	-.23032	-.25882	-.28709	-.58263	-.85114	-.98673		
42		.74130	.41611	.03010	0	-.03010	-.36063	-.69958	-.92224		
43		.89865	.64511	.28846	.25882	.22893	-.11567	-.50677	-.80756		
44		.98517	.82669	.52706	.50000	.47244	.13667	-.28412	-.64890		
45		.99404	.94746	.72954	.70711	.68394	.38028	-.04472	-.45492		
46		.92455	.99856	.88204	.86603	.84907	.59969	.19732	-.23619		
47		.78220	.97624	.97409	.96593	.95666	.78092	.42772	-.00459		
48		.57819	.88212	.99941	1.00000	.99941	.91241	.63292	.22726		
49		.32860	.72312	.95624	.96593	.97442	.98582	.80083	.44673		
50		.05312	.51096	.84756	.86603	.88338	.99644	.92154	.64189		

source are uniformly distributed from +0.05 to -0.05 feet, this introduces a random noise with a standard error σ of 0.88 cm.

Let σ_x represent the standard error of the random noise and σ_X the corresponding quantity after filtering. It can be shown that the filter response factor for random errors is given by

$$F_R^2 \equiv (\sigma_X/\sigma_x)^2 = \sum_{i=-N}^{N} w_i^2 \quad \ldots\ldots\ldots\ldots\ldots\ldots (15)$$

If all the 2N + 1 weight factors are equal and satisfy (2), then (15) reduces to the familiar relation

$$F_R = (2N + 1)^{-0.5}$$

for the tidal constituents

K_2	S_2	L_2	M_2	ν_2	N_2	μ_2	$2N_2$	M_3	MS_4	$2MS_6$	$2(MS)_8$
30.0821373	30.0000000	29.5284789	28.9841042	28.5125831	28.4397295	27.9682084	27.8953548	43.4761563	58.9841042	87.9682084	117.9682084
11.967	12.000	12.192	12.421	12.626	12.658	12.872	12.905	8.280	6.103	4.092	3.052
.1151	.4227	.0251	.9085	.0341	.1759	.0219	.0235	.1000	.1000	.0500	.0500
.0066	.0894	.0003	.4127	.0006	.0154	.0002	.0003	.0050	.0050	.0012	.0012
.86531	.86603	.87011	.87475	.87871	.87932	.88321	.88381	.72566	.51528	.03546	-.46898
.49752	.50000	.51419	.53039	.54427	.54641	.56012	.56221	.05317	-.46898	-.99749	-.56012
-.00429	0	.02469	.05317	.07780	.08161	.10618	.10998	-.64849	-.99859	-.10618	.99435
-.50496	-.50000	-.47123	-.43737	-.40753	-.40289	-.37255	-.36782	-.99435	-.56012	.98996	-.37255
-.86959	-.86603	-.84472	-.81836	-.79402	-.79014	-.76426	-.76015	-.79462	.42137	.17638	-.64491
-.99996	-1.00000	-.99878	-.99435	-.98789	-.98668	-.97745	-.97581	-.15890	.99435	-.97745	.97745
-.86096	-.86603	-.89338	-.92126	-.94213	-.94507	-.96233	-.96471	.56400	.60336	-.24570	-.27189
-.49004	-.50000	-.55589	-.61741	-.66782	-.67536	-.72241	-.72941	.97745	-.37255	.96003	-.72241
.01290	0	-.07400	-.15890	-.23153	-.24263	-.31376	-.32461	.85459	-.98729	.31376	.94950
.51236	.50000	.42712	.33941	.26094	.24864	.16818	.15564	.26283	-.64491	-.93778	-.16818
.87381	.86603	.81728	.75270	.69010	.67992	.61084	.59971	-.47314	.32268	-.38026	-.79176
.99985	1.00000	.99513	.97745	.95187	.94708	.91082	.90441	-.94950	.97745	.91082	.91082
.85656	.86603	.91447	.95735	.98273	.98566	.99804	.99894	-.90490	.68464	.44484	-.06256
.48252	.50000	.59624	.69745	.77521	.78634	.85214	.86132	-.36380	-.27189	-.87927	-.85214
-.02150	0	.12313	.26283	.37963	.39721	.50719	.52354	.37690	-.96484	-.50719	.86183
-.51973	-.50000	-.38197	-.23762	-.10802	-.08778	.04378	.06408	.91082	-.72241	.84331	.04378
-.87795	-.86603	-.78784	-.67854	-.56948	-.55157	-.42988	-.41026	.94498	.22036	.56698	-.90289
-.99967	-1.00000	-.98905	-.94950	-.89279	-.88225	-.80311	-.78926	.46065	.94950	-.80311	.80311
-.85206	-.86603	-.93332	-.98262	-.99954	-.99998	-.98875	-.98484	-.27643	.75816	-.62393	.14960
-.47496	-.50000	-.63514	-.76960	-.86382	-.87635	-.94343	-.95156	-.86183	-.16818	.75886	-.94343
.03010	0	-.17196	-.36380	-.51856	-.54121	-.67775	-.69714	-.97437	-.93148	.67775	.73529
.52706	.50000	.33590	.13312	-.04751	-.07543	-.25374	-.28070	-.55230	-.79176	-.71081	.25374
.88204	.86603	.75648	.59670	.43506	.40855	.22952	.20096	.17282	.11553	-.72814	-.97330
.99941	1.00000	.98056	.91082	.81210	.79393	.65918	.63593	.80311	.91082	.65918	.65918
.84756	.86603	.94991	.99677	.99215	.98767	.93486	.92310	.99275	.82311	.77489	.35503
.46737	.50000	.67250	.83305	.93152	.94303	.99217	.99576	.63769	-.06256	-.60422	-.99217
-.03870	0	.22037	.46065	.64492	.67076	.81773	.83700	-.06725	-.88758	-.81773	.57560
-.53435	-.50000	-.28898	-.02714	.20190	.23663	.45228	.48374	-.73529	-.85214	.54625	.45228
-.88606	-.86603	-.72328	-.50812	-.29012	-.25464	-.01881	.01806	-.99990	.00941	.85647	-.99982
-.99908	-1.00000	-.96968	-.86183	-.71174	-.68445	-.48551	-.45183	-.71588	.86183	-.48551	.48551
-.84296	-.86603	-.96417	-.99966	-.96073	-.94905	-.83880	-.81670	-.03907	.87876	-.89090	.54443
-.45977	-.50000	-.70820	-.88708	-.97666	-.98459	-.99617	-.99179	.65918	.04378	.42235	-.99617
.04730	0	-.26825	-.55230	-.75568	-.78249	-.92084	-.93638	.99575	-.83364	.92084	.38994
.54161	.50000	.24138	-.07916	-.35138	-.39152	-.63042	-.66338	.78598	-.90289	-.35705	.63042
.89001	.86603	.68832	.41380	.13814	.09395	-.19274	-.23621	.14496	-.09682	-.94616	-.98125
.99867	1.00000	.95643	.80311	.59416	.55673	.28997	.24587	-.57560	.80311	.28997	.28997
.83830	.86603	.97609	.99124	.90606	.88515	.70493	.67079	-.98033	.92447	.96672	.70928
.45211	.50000	.74219	.93108	.99816	.99992	.95524	.93983	-.84718	.14960	-.22141	-.95524
-.05587	0	.31547	.63769	.84813	.87336	.98242	.99046	-.24920	-.77029	-.98242	.18670
-.54880	-.50000	-.19319	.18457	.49238	.53599	.78012	.81092	.48551	-.94343	.15174	.78012
-.89390	-.86603	-.65167	-.31479	.01717	.06925	.39559	.44291	.95383	-.20197	.99318	-.91843
-.99819	-1.00000	-.94086	-.73529	-.46218	-.41420	-.08133	-.02801	.89880	.73529	-.08133	.08133
-.83358	-.86603	-.98563	-.97162	-.82944	-.79767	-.53926	-.49242	.35062	.95973	-.99894	.84214
-.44442	-.50000	-.77436	-.96455	-.99549	-.98862	-.87122	-.84241	-.38994	.25374	.01049	-.87122
.06446	0	-.36192	-.71588	-.92006	-.94095	-.99969	-.99662	-.91655	-.69823	.99969	-.02497
.55598	.50000	.14453	-.28788	-.62144	-.66617	-.89464	-.91923	-.94027	-.97330	.06039	.89464
.89772	.86603	.61344	.21223	-.17208	-.23061	-.58062	-.62821	-.44809	-.30481	-.99541	-.81418
.99763	1.00000	.92299	.65918	.31903	.26062	-.13098	-.19120	.28997	.65918	-.13098	-.13098
.82879	.86603	.99277	.94100	.73274	.68895	.34926	.29023	.86891	.98413	.98612	.93703
.43669	.50000	.80465	.98712	.96871	.95098	.74791	.70424	.97110	.35503	.20091	-.74791

The autocorrelation of random errors is given by

$$\begin{aligned} \psi_x(\tau) &= \sigma_x^2 & \tau &= 0 \\ &= 0 & \tau &= 1, 2, \ldots \end{aligned} \qquad \ldots\ldots\ldots\ldots\ldots (16)$$

and the complete autocorrelation of the noise (tidal plus random) is then

$$\psi_u(\tau) = (1/2) \sum_j c_j^2 \cos n_j \tau + \psi_x(\tau) \qquad \ldots\ldots\ldots\ldots\ldots (17)$$

x being uncorrelated to z.

Table 3--Table of $\psi_u(\tau)$ for the diurnal constituents, the semi-diurnal constituents, the shallow-water constituents, random errors, and the total noise, respectively; the latter is plotted in Figure 1

τ	Diurnal	Semi-Diurnal	Higher Species	Random Errors	Total Noise
0	.232100	.525500	.012400	.000240	.770240
1	.224513	.458915	.005684	0	.689112
2	.202249	.276052	-.003948	0	.474353
3	.166772	.023280	-.007170	0	.182882
4	.120411	-.235311	-.007031	0	-.121931
5	.066211	-.434178	-.002428	0	-.370395
6	.007728	-.522943	.004177	0	-.511038
7	-.051202	-.479179	.005216	0	-.525165
8	-.106721	-.314071	.003310	0	-.417482
9	-.155193	-.069551	.000852	0	-.223892
10	-.193450	.192350	-.003238	0	-.004338
11	-.219005	.405262	-.002159	0	.184098
12	-.230203	.515301	.002326	0	.287424
13	-.226337	.494717	-.000643	0	.267737
14	-.207692	.348905	-.005256	0	.135957
15	-.175520	.114968	-.002514	0	-.063066
16	-.131961	-.147699	.002007	0	-.277653
17	-.079892	-.372532	.005424	0	-.447000
18	-.022750	-.502673	.007051	0	-.518372
19	.035709	-.505347	.001839	0	-.467799
20	.091653	-.380127	-.005372	0	-.293846
21	.141423	-.158984	-.007834	0	-.025395
22	.181784	.101893	-.007269	0	.276408
23	.210116	.336388	-.000600	0	.545904
24	.224612	.485222	.010152	0	.719986
25	.224374	.510938	.010435	0	.745747
26	.209474	.407365	.000960	0	.617799
27	.180948	.201053	-.005065	0	.376936
28	.140723	-.055513	-.006739	0	.078471
29	.091488	-.297283	-.005124	0	-.210919
30	.036508	-.463162	.000730	0	-.425924
31	-.020585	-.511440	.003783	0	-.528242
32	-.076040	-.430290	.002826	0	-.503504
33	-.126227	-.240671	.002383	0	-.364515
34	-.167886	.009112	-.000257	0	-.159031
35	-.198330	.255699	-.002072	0	.055297
36	-.215628	.436784	.001833	0	.222989
37	-.218716	.506851	.001732	0	.289867
38	-.207478	.448634	-.004900	0	.236256
39	-.182738	.277353	-.006052	0	.088563
40	-.146202	.036741	-.001171	0	-.110632
41	-.100343	-.212143	.003849	0	-.308637
42	-.048232	-.406405	.008170	0	-.446467
43	.006671	-.497245	.006364	0	-.484210
44	.060741	-.462184	-.001714	0	-.403157
45	.110433	-.310668	-.006904	0	-.207139
46	.152517	-.081482	-.008422	0	.062613
47	.184282	.167160	-.005936	0	.345506
48	.203724	.372426	.004431	0	.580581
49	.209657	.482748	.011573	0	.703978
50	.201799	.470795	.005974	0	.678568

We must now choose a value for σ_x consistent with the relative importance we wish to place on the suppression of random errors and of tide. If we suppose that the tidal range is eight feet and the standard error 0.05 ft, we find that

$$\sigma_x^2 / \psi_z(o) \simeq 0.0003$$

According to Table 1, $\psi_z(o) = 0.77$ and hence $\sigma_x^2 \simeq 0.00024$. This value has been used in the computations.

Computations--The function $\psi_u(\tau)$ is plotted in Figure 1. It includes the separate effects of the diurnal, semi-diurnal, and shallow-water constituents, and of random errors. The constants entering (17) are given in Table 2 and the separate contributions from the three tidal species are given in Table 3. The value of $c^2/2$ was taken to be zero in some cases where its actual computed value was very small. This was done for three of the constituents listed in Table 2 and for all others not listed. In all, eight diurnal, eight semi-diurnal and four higher-species tidal constituents went into the computation of ψ_z.

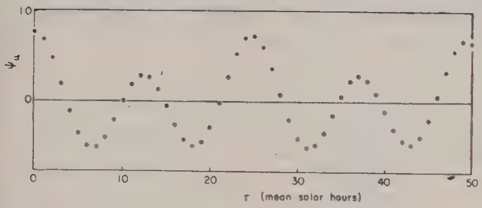

Fig. 1--Plot of the autocorrelation function $\psi_u(\tau)$ of the noise which is minimized in determining the weight factors

Having now specified the function ψ_u, the coefficients to (12) can be evaluated and w_i determined. These equations comprise a linear algebraic system of N equations in N unknowns. It is obvious that the larger the value of N the more effectively the minimization of $\psi_U(o)$ can be carried out. Let us consider $\psi_U(o)$ to be a function of N denoted by $\psi_U(o)_N$, and hypothetically determine the set of w_i for the case N equal to a certain value N_o. By (11), $\psi_U(o)_{No}$ can be evaluated. Let us now consider the set of w_i determined by letting $N = N_o + 1$. If the w_i determined in this latter case were exactly the same as in the previous case for $i = 1, 2, \ldots, N_o$, with $w_{No+1} = 0$, we would obtain the relation

$$\psi_U(o)_{No} = \psi_U(o)_{No+1}$$

However, since the determination of w_i is a minimizing process, its value must be equal to or less than its value for any particular arbitrarily chosen set of w_i. Therefore, we have the relation

$$\psi_U(o)_{N+1} \leq \psi_U(o)_N \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(18)}$$

Once it is decided for which value of N the solution of (12) is to be carried out, the determination of w_i for all lesser values of N can be made without additional labor by using the elimination method of solving the linear algebraic equations. The maximum N value actually used was 25, necessitating the computation of the function up to the value $\tau = 50$. The result of this is to give sets of weight factors for all values of N equal to or less than 25, which correspond to weighted averages taking into account 51, 49, 47, . . . , consecutive values of y. The filters corresponding to $N \leq 6$ are not of much practical interest and are not given. The computations were performed on IBM automatic computers.

After the computations were done, it was found that the condition (18) was violated at one stage, indicating that a numerical error had crept in. The error was found to be a small discrepancy in the value of cos (8n) for the constituent P_1, an identical error having been made independently by two persons. After this error was corrected, solutions were obtained which satisfied (18) at all stages, and which also gave lower values of the quantity $\psi_U(o)_N$ for all N than the previous wrong solution. For the most part, however, the correct solutions are surprisingly little more effective than the corresponding wrong solutions although the corresponding sets of w_i differ considerably.

Results--Table 1 gives the weight factors and characteristics of all the filters that have been discussed.

The first row gives the filter factor, F_D, of the composite diurnal tide, defined as

$$F_D = \left\{ \sum_j F^2(n_j)\, c_j^2 \Big/ \sum_j c_j^2 \right\}^{0.5} \quad \ldots\ldots\ldots\ldots\ldots \text{(19)}$$

taking into account only the diurnal constituents. In the same manner F_S and F_H denote the filter factors for the composite semi-diurnal tide and for the composite higher-species tide. These quantities were computed on the basis of the constituents listed in Table 2. F_R is the filter factor for random errors according to (15), and F_2 is the filter factor for a component whose period is two days.

The mean square noise output for any given situation can then be approximated by

$$\psi_U(o) = (1/2)F_D^2 \sum_D H_j^2 + (1/2)F_S^2 \sum_S H_j^2 + (1/2)F_H^2 \sum_H H_j^2 + F_R^2 \sigma_x^2 \qquad \ldots\ldots\ldots\ldots (20)$$

according to the above definitions. The success of the approximation depends on the tidal constituents of a species having amplitudes proportional to their equilibrium values. For this reason the third term of (20) is greatly in doubt. If the shallow-water tide is important and it is desirable to obtain a better estimate to $\psi_U(o)$, the third term of (20) should be replaced by

$$(1/2) \sum_H F^2 (n_j) H_j^2$$

The response factor for the filters D_{21}, B_{39} and C_{51} is shown in Figures 2, 3, and 4. This is essentially (3) plotted against period instead of speed, n.

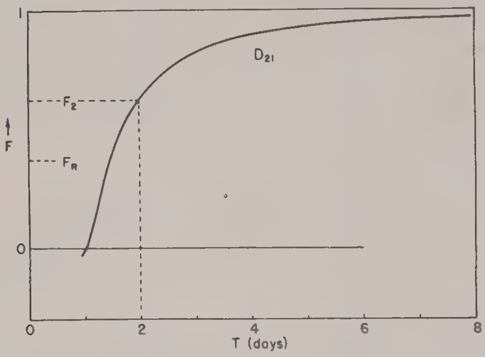

Fig. 2--Plot of F(T) for the filter D_{21}

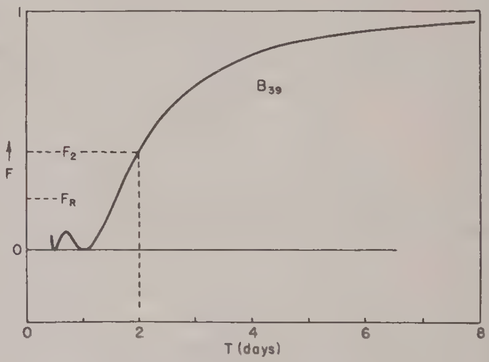

Fig. 3--Plot of F(T) for the filter B_{39}

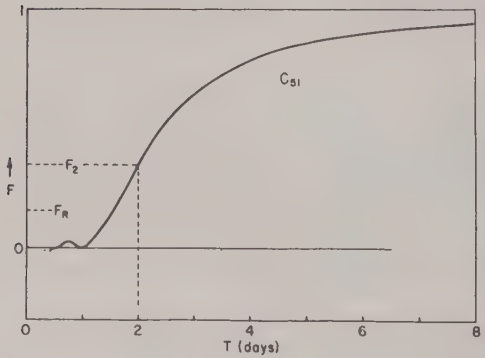

Fig. 4--Plot of F(T) for the filter C_{51}

The following examples illustrate the selection and use of the filters for any particular problem:

Example a--A tide gauge was established at station A and only 28 consecutive hourly tidal values were obtained before a storm washed out the installation. It is desired to obtain the best possible estimate of mean sea level (eliminating tidal effect) during that time. The tide at station A is known to be predominantly semi-diurnal, having a mean range of about five feet, with the diurnal tide contributing only about one foot. The quantity of data restricts us to a filter using 28 or less ordinates, that is, one which has a subscript of 28 or less. We shall first select the filter that has the smallest possible filter factor, F_S, for the predominant semi-diurnal tide. According to Table 1, this is D_{25}, for which $F_S = 0.00215$. The maximum residue of the semi-diurnal and diurnal tides are (0.00215)5′ = 0.3 cm, and (0.0301)1′ = 0.9 cm respectively, the diurnal residue being the larger. One might think that filter D_{27} would be better since it cuts down the diurnal tide more than D_{25}. For D_{27} we obtain for the maximum residue of the semi-diurnal and diurnal tides, respectively, (0.00526)5′ = 0.8 cm and (0.0248)1′ = 0.8 cm. Evidently the use of filter D_{25} will give a lower total residue. If random errors or the shallow-water tides give an appreciable residue, then they should be taken into account.

Example b--A sea-level study is to be made at station B, where the root mean square values of the diurnal and semi-diurnal tides $(0.5 \Sigma H_j^2)^{0.5}$ are known to be one meter and two meters, respectively. The hourly tidal heights have been rounded off to tenths of feet giving rise to a standard error of 0.88 cm. Other random errors and the shallow-water tides are negligible. We wish to use the 'shortest' possible filter that will satisfy the requirement that the residual output of the tide (diurnal and higher) plus random errors have a rms value, r, of less than 2 mm. Hence

$$r^2 \equiv (1/2)[(100\,\text{cm})^2 F_D^2 + (200\,\text{cm})^2 F_S^2] + (0.88\,\text{cm})^2 F_R^2 \le 0.04\,\text{cm}^2$$

The values of r^2 for various filters are shown in Table 4.

Table 4--Values of r^2 for various filters

Filter	r^2 (cm^2)
D_{33}	0.460
D_{35}	0.085
D_{37}	0.040
D_{39}	0.031
B_{39}	0.065
D_{41}	0.028
D_{43}	0.026
D_{45}	0.023
D_{47}	0.022
D^*_{47}	0.030
D_{49}	0.022
D^*_{49}	0.094
D_{51}	0.025

The filter D_{37} thus satisfies our requirements. For shorter filters the residual noise rapidly increases. If instead we had wanted to reduce the residual noise as much as possible regardless of the expense, then D_{47} would have been our choice.

Two considerations make it desirable to use the shortest filter satisfying the requirements of the problem: (1) computational labor, and (2) the filter's attenuation of that portion of the spectrum which we want to study. The value of F_2 is a useful guide in the latter consideration, as it is an index of the filter's response to periodicities just longer than those of the diurnal tide.

Table 1 indicates that the value of F_2 generally decreases with the length of filter. The reason for this is clear. For the D series of filters the minimization process was carried out without regard to the F_2 value, and the longer filters have a tendency to average out (attenuate) longer periodicities. Even for the worst case, however, the value of F_2 is sufficiently large to indicate that variations having periods of as little as two days can be satisfactorily studied with the filter.

Since the D filters were determined by minimizing an expression like (20), we should expect that $\psi_U(o)$ decreases with N but not that the magnitude of the individual terms of (20) decreases with N. In fact they do not. For this reason some of the filters determined using the numerical error actually have better values of one or more of the quantities F_D, F_S, or F_R than the corresponding 'correct' filters. Four of these are thought to be of possible use and are included in Table 1 marked with an asterisk.

It has been noticed that for filters larger than D_{35} the noise is largely due to random errors, and any subsequent improvement is essentially a $\sqrt{2N + 1}$ reduction of these errors. This indicates that in order to reduce the residual noise even further it might be necessary to collect more accurate data. A better filter could then be obtained by placing less emphasis on the random errors.

With regard to the comparative effectiveness of the filters determined by the minimization criterion and those not, it is seen that the former are in every case superior, as was to be expected, to the filters A, B, C, and D* if the comparison is made between filters taking the same number of y values into the average.

Acknowledgments--The author would like to express his thanks to Walter Munk for his advice and encouragement of this study, to Carl Eckart for his advice and suggestions, to Robert Arenz and Dorothy Shumway of the U. S. Navy Electronics Laboratory at San Diego for solving numerically the set of linear algebraic equations with their IBM automatic computing machines, and to Margaret DeSelle and Janet Osborn for their help with the manual computations. This paper represents in part results of research carried out by the University of California under contract with the Office of Naval Research.

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(Communicated manuscript received June 6, 1955;
open for formal discussion until May 1, 1956.)

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PROCEEDINGS OF THE NATIONAL ACADEMY OF SCIENCES
Vol. 41, No. 11, November 1955

A DISCREPANCY BETWEEN CALCULATION AND MEASUREMENT OF SUBMARINE ILLUMINATION

By Elizabeth M. Kampa

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Communicated by Carl L. Hubbs, August 5, 1955

An investigation of the behavior of the sonic-scattering layer in the region of the San Diego Trough has proved that it is closely associated with the degree of submarine illumination.[1] This finding could not have been predicted by extrapolating from light measurements made in surface layers in this area. Such measurements were made by Richardson[2] with a sodium-vacuum phototube at midday in August, 1930 (Fig. 1, *broken line*). Extrapolation from these data would yield values of light intensity indicated by the open circles in Figure 1.

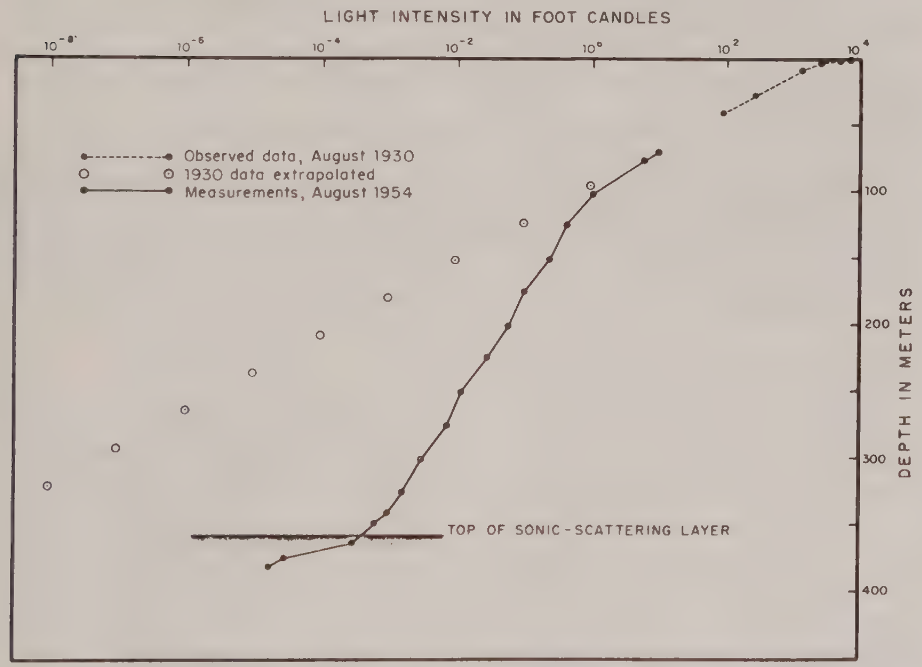

FIG. 1.—Decrease of light intensity with depth in the San Diego Trough. The 1930 data are taken from Richardson. The sonic-scattering layer was detected with an EDO echo-sounder.

The development of multiplier phototubes and their recent incorporation into submarine photometric techniques have made such extrapolation unnecessary. The penetration of daylight into Californian coastal waters is being studied by means of highly sensitive submarine photometers designed by James M. Snodgrass, of Scripps Institution.[3] Each employs a 931-A photomultiplier tube and is equipped with a Depth Telerecording Unit.[4]

Actual measurements of submarine illumination in the San Diego area at midday in August, 1954, yield the curve (*solid line*) shown in Figure 1. It is obvious that at a depth of 300 meters the calculated intensity may differ from the measured intensity by as many as five orders of magnitude. In the San Diego Trough during summer the intensity of illumination declines rapidly in the upper 75–125 meters. The vertical extent of this layer of optically dense water appears to be consistent with the vertical extent of the euphotic zone in this area. Below about 100 meters, a layer of much clearer water with an extinction coefficient comparable to those obtained by Clarke[5] for the Caribbean is commonly encountered.

When a well-defined sonic-scattering layer is present, a second inflection of the light-depth curve may be observed as the photometer enters the layer. The maximum depth to which the photometer could be lowered in August, 1954, was determined by the amount of electric cable available. In July, 1955, with a longer cable, further data were obtained which indicate that below the scattering layer the water is as clear as it is above the layer.

These studies are being carried out under contract between the Office of Naval Research and the Scripps Institution.

* Contributions from the Scripps Institution of Oceanography, New Ser., No. 810.

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[2] B. Richardson, "Photo-electric Measurements of the Penetration of Light in Sea-Water, and the Results of Laboratory Photo-electric Measurements of the Absorption Coefficient of Sea-Water" (unpublished).

[3] J. M. Snodgrass, R. F. Devereux, and J. H. Cawley, "A Telerecording Bathyphotometer" (in press).

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BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
VOL. 66, PP. 1489-1498, 6 FIGS. 2 PLS. DECEMBER 1955

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DELTA-FRONT VALLEYS BORDERING THE MISSISSIPPI DISTRIBUTARIES

By Francis P. Shepard

Abstract

Shallow discontinuous valleys crease the upper portion of the continental slopes in the region where the Mississippi Delta has built across the shelf. These valleys attest to the instability of the forward-growing slope despite its average inclination of only 1 per cent. Mass movements probably of the earthflow type appear to be the cause of the valleys rather than turbidity currents because deposits from valley floors show no concentration of sand by currents, and many of the valleys are not located at points where large discharge of sediment-laden water could produce turbidity currents. Furthermore, depressions and hills along the courses of the valleys and their short length differentiate them from the long continuous slightly incised valleys which are outer continuations of submarine canyons and which are generally ascribed to turbidity currents. The delta-front valleys shift position as the slopes are built forward.

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Introduction

During the study of marine sedimentation bordering the Mississippi Delta, which constitutes one of the objectives of a grant from the American Petroleum Institute (Proj. 51), the writer had an opportunity to investigate the shallow submarine valleys found in the slopes bordering the most advanced portions of the Mississippi Delta. These valleys are clearly shown in the unpublished hydrographic sheets of the U. S. Coast and Geodetic Survey. Interest in such valleys stems partly from discussions of the origin of submarine canyons. Shallow valleys cutting the submerged delta fronts in the lakes of Switzerland have been attributed by Daly (1936, p. 413–418) to erosion by turbidity currents. The shallow valleys found as the outer extensions of submarine canyons have been compared to those of the Swiss

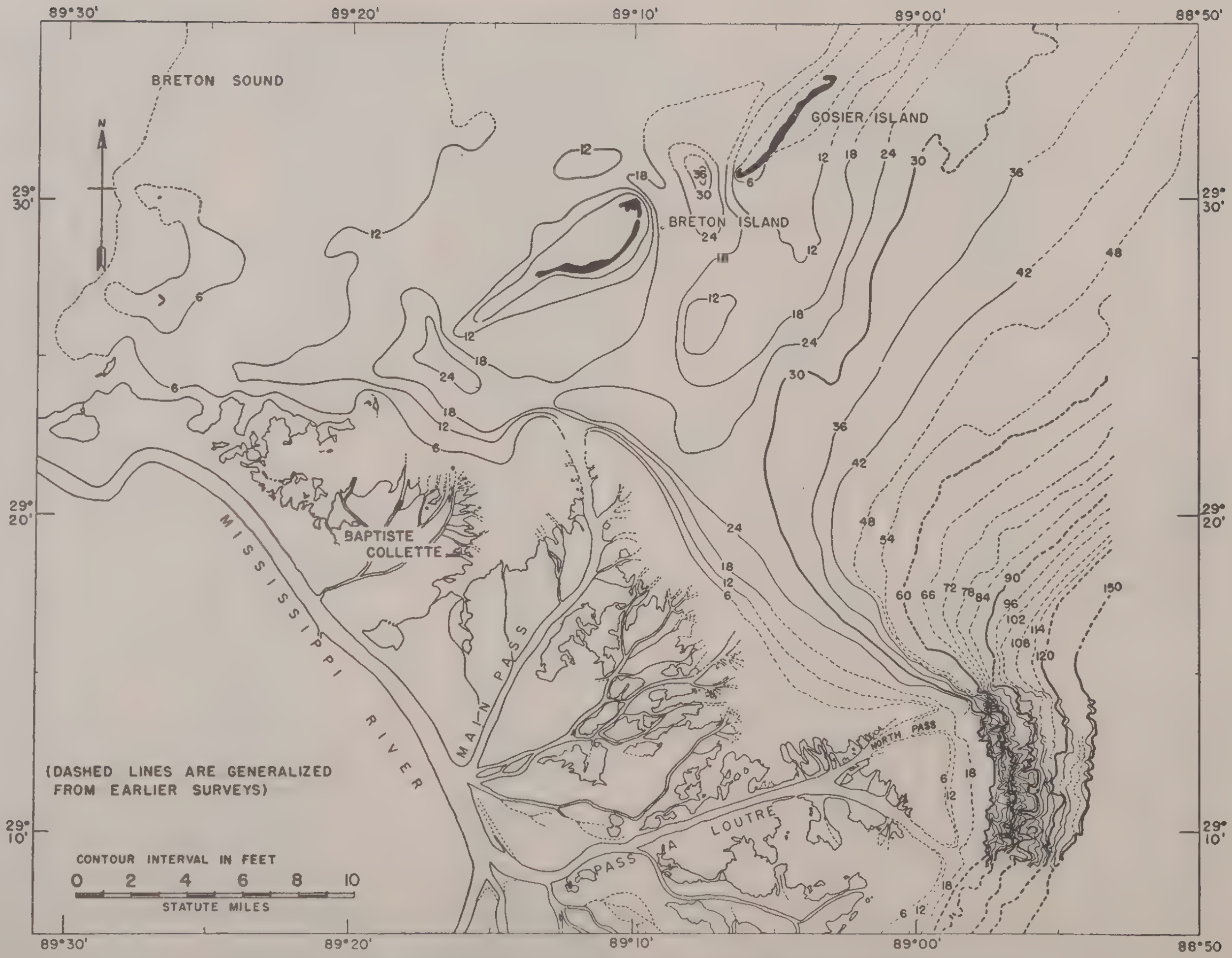
89°30'
89°20'
89°10'
89°00'
88°50'
29° 30'
29° 20'
29° 10'
N
BRETON SOUND
GOSIER ISLAND
BRETON ISLAND
BAPTISTE COLLETTE
MISSISSIPPI RIVER
MAIN PASS
NORTH PASS
PASS A LOUTRE
(DASHED LINES ARE GENERALIZED FROM EARLIER SURVEYS)
CONTOUR INTERVAL IN FEET
0 2 4 6 8 10
STATUTE MILES
6
12
18
24
30
36
42
48
54
60
66
72
78
84
90
96
102
108
114
120
150

FIGURE 1.—SUBMARINE TOPOGRAPHY OFF NORTHEAST PORTION OF BIRDFOOT DELTA

deltas (Shepard, 1952, p. 88) and similar valleys called deep-sea channels have been found on the deep floor of the Atlantic (Ewing *et al.*, 1953), the Pacific (Menard, 1955; Dill *et al.*, 1954), and of the Indian Ocean (Dietz, 1953). All these deep valleys have also been attributed to turbidity currents.

The shallow valleys bordering the Mississippi Delta offered the best available opportunity of obtaining sounding details which would allow the construction of comparatively accurate contours. Furthermore, the Scripps surveys compared to earlier soundings served to show the changes in the valleys accompanying the forward building of the delta front. It was appreciated, however, that evidence concerning the origin of the Mississippi Delta valleys would not necessarily apply either to the valleys of the Swiss Lakes nor to the deep-sea channels of the ocean basins.

ACKNOWLEDGMENTS

Appreciation is expressed to P. C. Scruton, J. R. Curray, G. A. Rusnak, and D. G. Moore for collecting some of the samples and for making some of the surveys on which the present paper is based, also to D. M. Poole and H. W. Lusk for their analyses of the sediment samples, and to J. R. Moriarty for the drafting. This investigation was supported by a grant from the American Petroleum Institute, Project 51.

DISTRIBUTION AND GENERAL CHARACTER OF THE VALLEYS

Charts of the Mississippi Delta area (Fig. 1; Pl. 1) indicate that the valleys extend from North Pass to Southwest Pass, but are poorly developed between South and Southwest Pass. No valleys are found around the rest of the delta. They are concentrated in the zone where the Mississippi Delta has built across the continental shelf, so that several distributaries are actually pouring their sediment-laden waters onto the continental slope. Despite the rapid growth of such distributaries as Main Pass and Baptiste Collette (Fig. 2), the valleys are missing off the distributaries on the northeast and southwest sides of the delta. Off these passes the river delta is growing out onto a relatively flat continental shelf. Off East Bay, between South and Southwest passes (Pl. 1), valley development is poor in the gap between major passes where the shelf is relatively broad, shallow, and indented. The valleys are developed best near South Pass and for about 3 miles east and west of that pass. The very prominent valley west of South Pass (Pl. 1) appears completely unrelated to any active pass, but the nineteenth century charts show that there was a prominent distributary, Grand Pass, near the head of this valley (Fig. 2). Like South Pass, Grand Pass had been built out to the edge of the shelf, and at one time these two distributaries constituted the most forward-built structures of the Mississippi Delta. Southwest Pass has been building diagonally out onto a broad ridge (Fig. 3).

Detailed soundings recorded on the unpublished hydrographic sheets of the U. S. Coast and Geodetic Survey show that these valleys are short and discontinuous, starting near the top of the slope and extending down to depths which rarely exceed 200 feet (Pl. 2)[1]. The valley floors lie from a few feet to about 50 feet below the adjacent ridges. The valleys have very few tributaries; most of them terminate in fanlike features, some have basin depressions along their courses, and a few have small hills.

Most of the valleys are about one-third to two-thirds of a mile wide. They commonly are 2–4 miles long. In some places valleys die out, and adjacent to the terminations others start in along the slope. Soundings outside this area are not so complete as those on which the valleys are based, but lines along the slope are sufficient to indicate that beyond the 200-foot contour valleys are inconsequential if they do exist.

The valleys have gradients of about 1 per cent near South Pass and have slightly gentler gradients off Southwest Pass and off Pass a Loutre. This gradient is approximately the same as the slope of the delta front in this area, and the same slope continues down to the deep parts of the Gulf of Mexico with little interruption. The walls of the valleys are steeper than the general gradient. In echo-sounding profiles taken by the Scripps A.P.I. project, slopes up to about 15° are indicated (Fig. 4). These same soundings show that the valley profiles include V shapes, flat floors with steep sides, and U shapes with an inner gorge. One valley has a small hill rising from the flat floor. Comparisons of the two sounding lines in Figure 4, which were made off the same area and separated by about 1500 feet, show that in the outer line two valleys are each about 6 feet deeper and the third has the same depth.

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[1] The soundings on which the contours are based are included, so that readers may make their own contour interpretations.

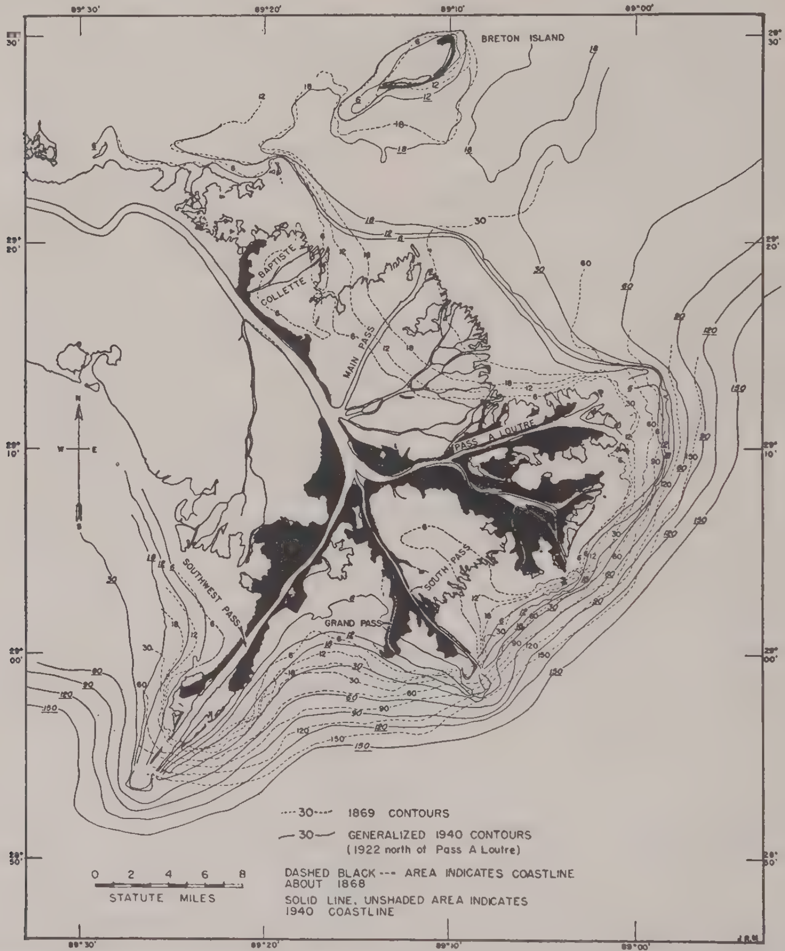
89°30'
89°20'
89°10'
89°00'
29° 30'
29° 20'
29° 10'
29° 00'
28° 50'
BRETON ISLAND
BAPTISTE
COLLETTE
MAIN PASS
PASS A LOUTRE
SOUTHWEST PASS
SOUTH PASS
GRAND PASS
N
W
E
S
---30--- 1869 CONTOURS
—30— GENERALIZED 1940 CONTOURS (1922 north of Pass A Loutre)
DASHED BLACK --- AREA INDICATES COASTLINE ABOUT 1868
SOLID LINE, UNSHADED AREA INDICATES 1940 COASTLINE
0 2 4 6 8
STATUTE MILES

FIGURE 2.—COMPARISON OF OLD AND NEW OUTER DELTA OF THE MISSISSIPPI RIVER, WITH GENERALIZED CONTOURS SHOWING THE DEPTH CHANGES SINCE APPROXIMATELY 1869

In seven localities cores 1–4 feet long were collected on the floor of the valleys and on adjacent ridges. Three were obtained during high-water stages of the Mississippi River, two directly after high water. In five of these pairs very similar material was found on ridge and valley, and the cores indicate no difference in the nature of sedimentation in the two environments. In the other two pairs the sediment was slightly more compact underneath the valley than on the adjacent ridge. The sediments of all 14 cores are silty clays or clayey silts characteristic of the delta front and all but one have thin interbedded sand laminae. The sand-silt-clay content of the top 20 cm of these cores is given in Table 1.

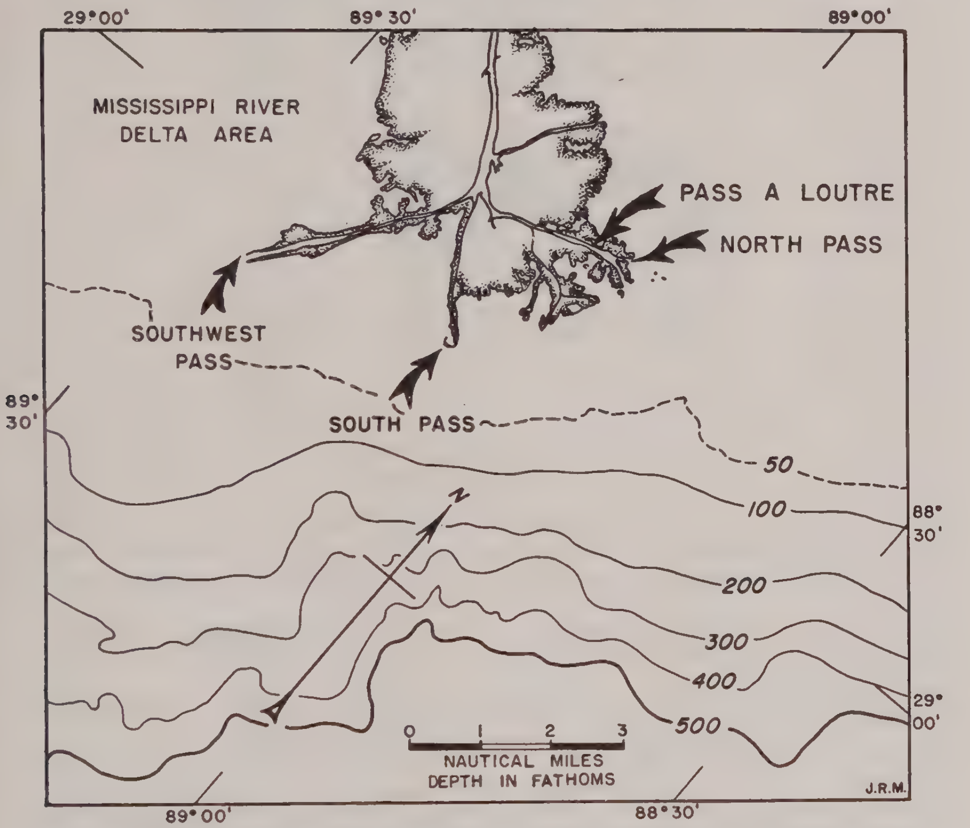

Figure 3.—Contours off the Mississippi Delta Showing how the Advanced Portions have Crossed the Continental Shelf

Relation to Forward-Growing Fore-Set Slopes

Comparison of profiles made off Pass a Loutre, South Pass, and Southwest Pass between 1860 and 1871 with profiles of the 1940 survey, covering approximately the same lines, shows that the slopes off these passes have been moving forward en masse about one-half to 2 miles (Fig. 5). The inclination of the slopes has remained about the same. This is also indicated in Figure 2 where the contours of the old survey are superimposed on generalized contours of the 1940 survey.[2]

A comparison between the 1940 survey and one made by Scripps Institution in 1953 and 1954 shows a distinct change here during the last 13 or 14 years (Fig. 6). Here, also, the whole slope has moved forward, and some valleys have changed position. At "A" in Figure 6 the 90-foot contour shows a ridge where there was a valley and just to the north a valley where there was a ridge. The same shift continues for a mile to the south. Elsewhere, however, the valleys have not changed position. At "B" some new valleys have formed and an old valley has been filled.

Origin of Delta-Front Valleys

Two hypotheses can be offered to explain the small valleys off the Mississippi Delta.

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[2] Valleys are omitted from the recent surveys to make meaningful this comparison because of the absence of sufficient soundings to show the valley pattern on the old surveys.

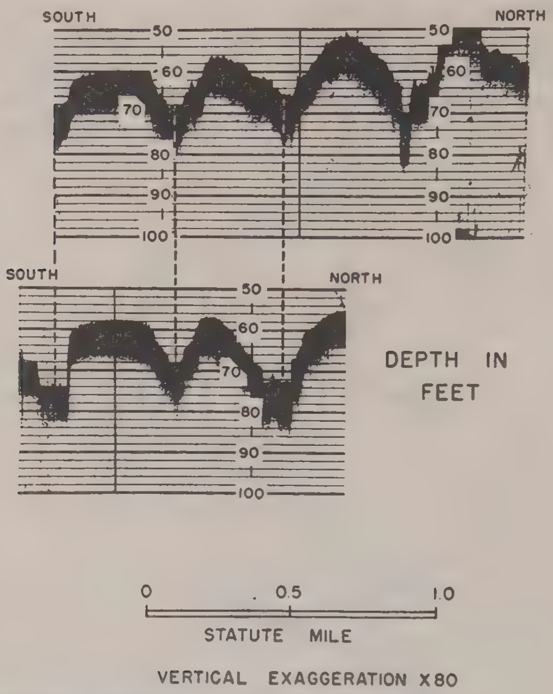

FIGURE 4.—FATHOGRAM PROFILES OF THE DELTA-FRONT VALLEYS OF PASS A LOUTRE
The two profiles are 1500 feet apart and show the changes in three valleys in that distance.

TABLE 1.—COMPARISON OF VALLEY AND RIDGE SEDIMENTS

Valley core					Ridge core					General location
Core nos.	Depth (feet)	Sand	Silt	Clay	Core nos.	Depth (feet)	Sand	Silt	Clay	
275A	37	0	40	60	275B	28	0	37	63	Off Pass a Loutre
519A	69	2	44	54	519B	60	1	42	57	Off Pass a Loutre
520A	60	0.1	55.9	44	520B	48	0.3	53.7	46	Off North Pass
704	54	1.7	52.7	45.6	705	42	0.8	53	46.2	Off South Pass
712	66	0.4	56	43.6	711	42	0.3	43	56.7	Off South Pass
746	68	0.1	39.1	60.8	747	58	0.2	47.2	52.6	Off Pass a Loutre
749	75	0.1	38.9	61.0	748	51	0.2	48.9	50.9	Off Pass a Loutre

One is that they were cut by turbidity currents generated by the large quantities of sediment coming from the active passes. As this sediment settles to the bottom of the water mass, density currents could cascade down the slope towards the deep floor of the Gulf of Mexico. These currents may be expected to flow every year during the high-water stages[3] of the Mississippi. If such currents are strong enough to be the cause of the valleys, however, they should concentrate the coarser sediments along the valley axes forming a sandy bottom, particularly since all the delta-front cores show that sands are available. Therefore, the finding of cores taken during high water with no sand concentrates at or near the surface renders doubtful a turbidity-current origin.

Other continental slopes show evidence that turbidity currents are capable of continuing

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[3] Owing to flood-control measures high water is almost the same in height, although not in duration, each year.

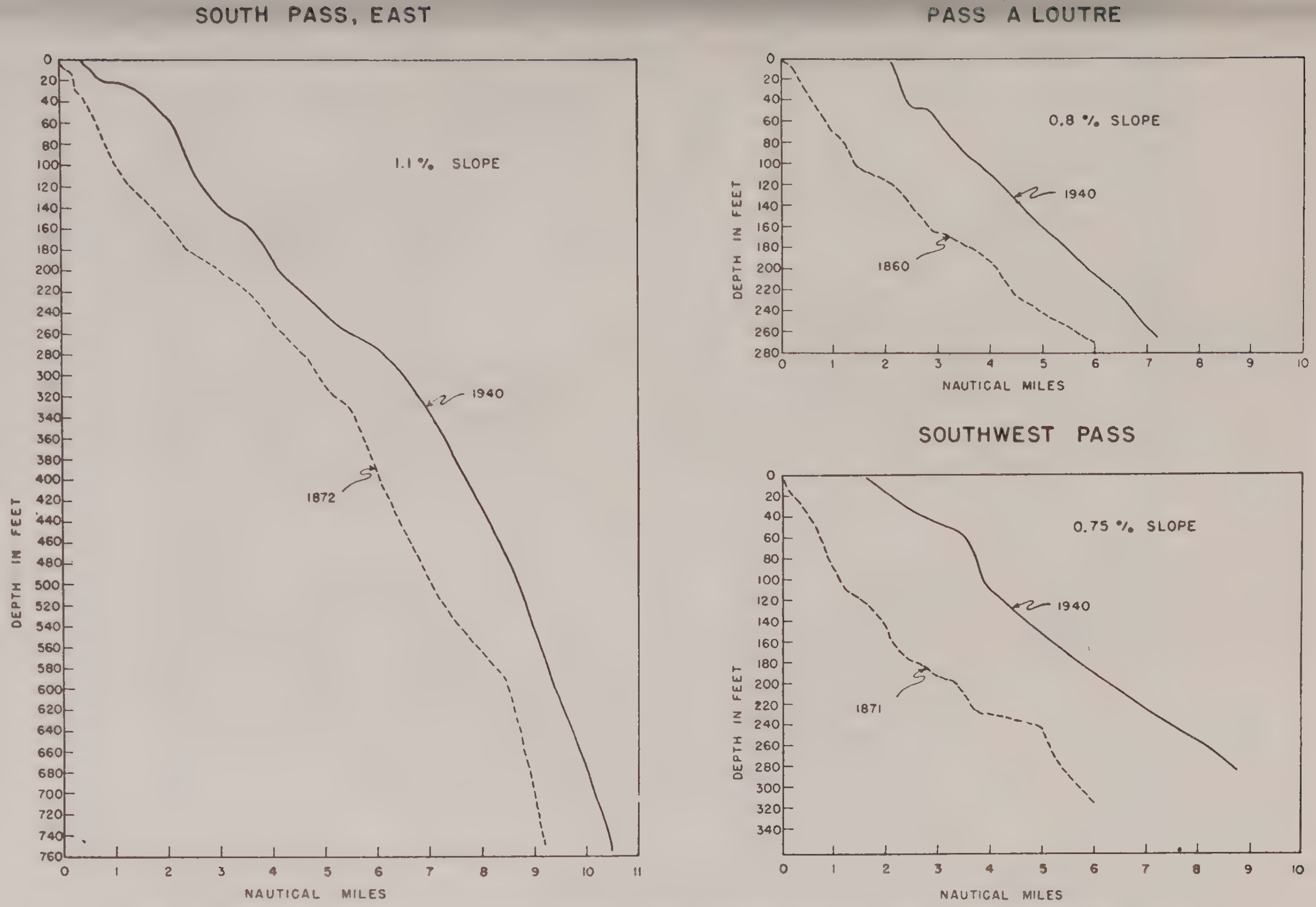

FIGURE 5.—PROFILES SHOWING THE FORWARD GROWTH OF THE SLOPE OFF THE MAIN PASSES OF THE MISSISSIPPI DELTA
Note that the slope has remained essentially constant off all passes.

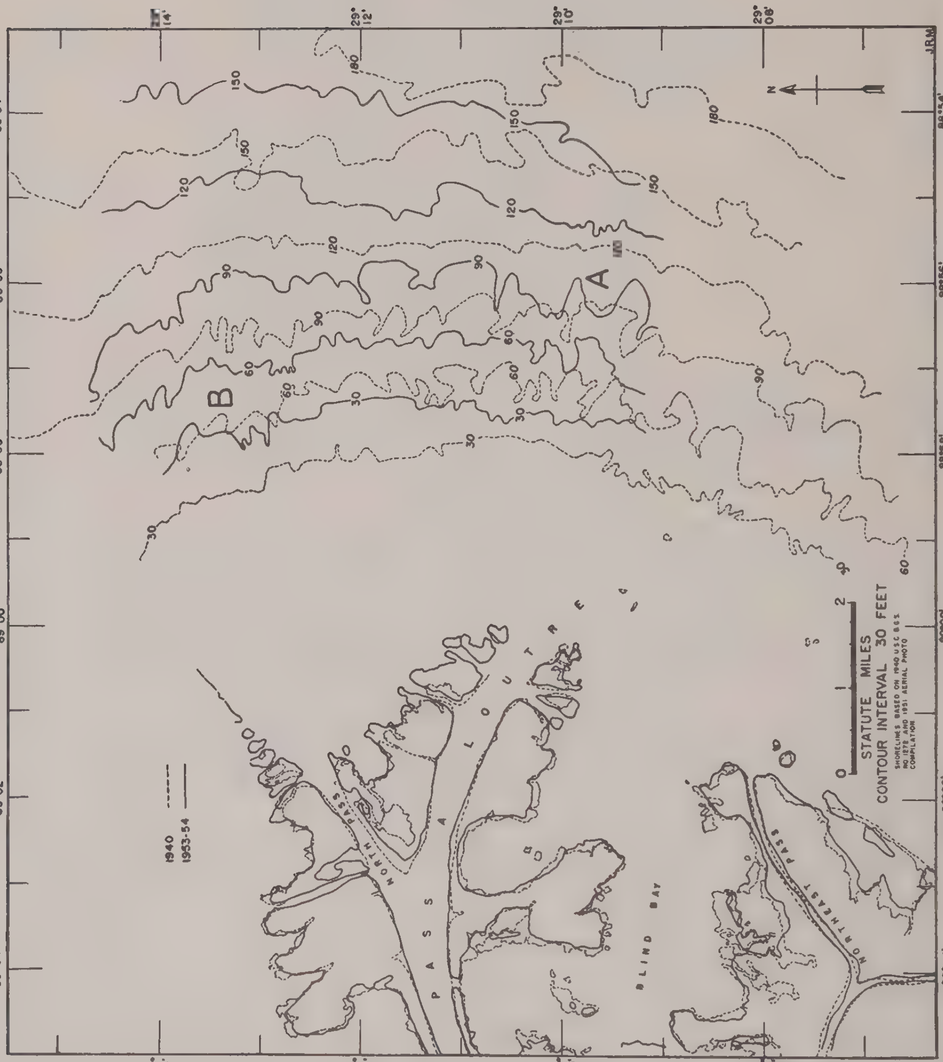
1940
1953-54
STATUTE MILES
0
1
2
CONTOUR INTERVAL 30 FEET
SHORELINES BASED ON 1940 USC&GS
NO 1272 AND 1951 AERIAL PHOTO
COMPILATION
N
A
B
30
60
90
120
150
180
PASS A LOUTRE
NORTH PASS
NORTHEAST PASS
BLIND BAY
29° 14'
29° 12'
29° 10'
29° 08'
88°54'
88°56'
88°58'
89°00'
89°02'
89°04'
JRM

Figure 6.—Depth Changes in Recent Years off Pass a Loutre and Vicinity, Based on a Comparison of 1940 Soun

to the base of the slopes. Valleys which form a continuation of submarine canyons and are generally attributed to turbidity currents show no tendency to stop along the slopes. In contrast, the Mississippi delta-front valleys do not extend far down the slope, which suggests another mechanism for their origin.

Furthermore, if turbidity currents were responsible for the valleys, they would be best developed directly outside the mouths of each of the principal distributaries. Figures 1 and 2, however, show no indication that the valleys are best or even well developed directly beyond the distributaries. For example, directly off the jetties of Southwest Pass valleys are very inconspicuous (Pls. 1, 2C), but to the southeast, where little muddy water would have impinged on the slope, valleys are well developed. Similarly, the best development of valleys around South Pass seems related to the flanks of the forward-moving delta front rather than to the distributary itself. The diagonal course of the large valley southwest of South Pass is also anomalous as turbidity currents are said to flow straight down slopes (Kuenen, 1953, p. 1297).

The presence of well-developed valleys off the old Grand Pass, which has now disappeared, and off the inactive Southeast and Northeast passes (Pl. 1) shows that an advancing slope is a more significant factor in producing the valleys than is the recent introduction of large amounts of muddy water into the area. Valleys caused by turbidity currents and related to passes would disappear off abandoned passes as the general slope grew forward.

The alternative hypothesis is that these delta-front depressions are slump valleys caused by some type of mass movement such as an earthflow (Sharpe, 1938, p. 50) in the fore-set slope. The very gentle inclination of the slope (as low as 0.75 per cent off Southwest Pass) might seem prohibitive of this hypothesis had not landslides been noted in water-saturated muds on slopes as low as 1 per cent (Ells, 1908). A sudden earthflow in the Lake of Zug in Switzerland in 1887 (Gilluly *et al.*, 1951, p. 237) left an underwater trench 20 feet deep and 1000 feet long. A debris tongue outside this flow is comparable to the fans outside the Mississippi Delta valleys.

The discontinuity of the valleys favors an earthflow, and their shifting position with time along the slope is equally favorable since the areas adjacent to a valley cut by landslides are likely to slide at some later time. The existence of mud lumps in front of the actively growing Mississippi passes has been explained by Morgan (1952, p. 138) as owing to plastic flow of the clay under the advancing bar of sandy silt.

The close relationship of angle of fore-set slope to the valley distribution indicates that the steeper slopes are unstable. As the delta builds forward, it evidently develops a slope which is greater than is compatible with the saturated clayey sediments. The valleys are best developed where the slope is slightly greater than 1 per cent off South Pass, and are concentrated on the relatively steep slope along the east flank of the bulge at Southwest Pass (Pl. 1), whereas they are very poorly represented on the gentler slopes to the west.

These considerations favor an earthflow or other type of landslide origin, although much of the displaced material may have continued down the slope, beyond the valley ends, as a turbidity current which was too weak to cut valleys.[4]

Relation to Origin of Deep Submarine Valleys

The evidence favoring an earthflow origin for the shallow valleys on the gentle slopes off the Mississippi Delta may apply also to the slightly incised valleys which extend down the slopes outside some major submarine canyons. (*See* Ericson *et al.*, 1951; Dill *et al.*, 1954; Menard and Ludwick, 1951; and Menard, 1953.) It has been suggested that these deep outer valleys could not be due to landslides since they are found on very gentle slopes, but this argument loses authority in view of the present study. Slides on the gentle slopes of the deep-sea floor could possibly account for some of the curious valleys found in these places.

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[4] K. O. Emery has recently informed the writer of evidence that a series of similar sea-floor valleys off the Palos Verdes Hills in southern California are also due to landslides which continued seaward as turbidity currents.

On the other hand, the shallow-valley continuations of the submarine canyons differ from the valleys off the Mississippi Delta. Sand is a common sediment on the floors of the former, and indicates strong currents. Furthermore, these deep outer valleys appear to slope continuously seaward in contrast to the short, discontinuous valleys bordering the Mississippi Delta.

The breaking of the cables during the Grand Banks earthquake has been attributed to turbidity currents by Heezen and Ewing (1952), who discarded a landslide hypothesis largely because the slopes seemed too gentle for landslides. The recent map of the outer cable-break area (Heezen *et al.*, 1954, Fig. 3), however, shows slopes of about the same inclinations as along the front of the Mississippi Delta. Furthermore, the mass movements indicated off the Mississippi Delta did not have the impetus of a large earthquake.

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MANUSCRIPT RECEIVED BY THE SECRETARY OF THE SOCIETY FEBRUARY 1, 1955.

CONTRIBUTION FROM THE SCRIPPS INSTITUTION OF OCEANOGRAPHY, New Series No. 811.

THE TRENCHES OF THE PACIFIC

The floor of the great ocean is incised with tremendous furrows. The bottoms of several are farther below sea level than Everest is above it. They are clues to the history of the earth's crust

by Robert L. Fisher and Roger Revelle

On April 28, 1789, Lieutenant William Bligh, commanding H.M.S. *Bounty*, had a memorable quarrel in the Pacific Ocean with his senior warrant officer, one Fletcher Christian, as a result of which they parted company and sailed off in opposite directions—Christian in the *Bounty* and Bligh in the ship's longboat. This historic mutiny took place near the great volcano of Tofua in the Friendly Islands, better known today as the Tonga Islands. Bligh and Christian were well acquainted with the fact that the oceanic topography around these islands was somewhat unusual—full of treacherous shoals and narrow interisland passages. But they could not know, for methods of deep-sea sounding had not yet been invented, how unusual it really was, nor that this place would one day yield one of the most remarkable discoveries in the history of ocean-going exploration.

Beneath the placid sea east of the Tonga Islands yawns a monstrous chasm nearly seven miles deep. A hundred years after the *Bounty* episode another British vessel first plumbed its depths. Surveying the ocean bottom around the islands, Pelham Aldrich, commanding H.M.S. *Egeria*, was surprised to find that on two occasions his sounding lead did not touch bottom until 24,000 feet of wire had been paid out. Aldrich's discovery prompted other nations to send out expeditions to explore the Tonga undersea abyss. Eventually they traced out a great trench running from the Tonga Islands south to the Kermadec Islands [*see map on page 40*]. The deepest sounding made recently by the research vessel *Horizon* of the Scripps Institution of Oceanography, is some 35,000 feet. The immense chasm plunges about 6,000 feet farther below sea level than Mount Everest rises above it!

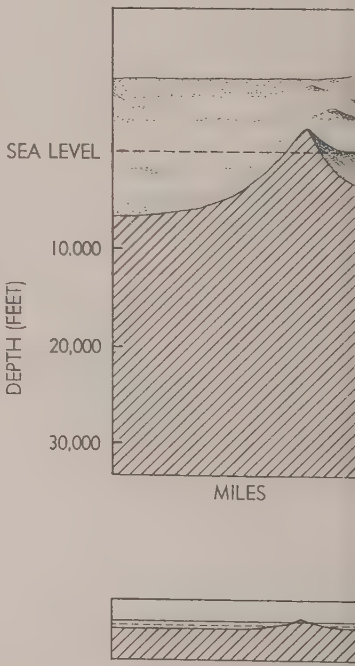
The Tonga-Kermadec Trench is now known to be but one member in a vast chain of deep, narrow trenches which lie like moats around the central basin of the Pacific [*see map*]. All of them parallel island archipelagoes or mountain ranges on the coasts of continents. Along the coast of South America, the drop from the top of the Andes to the bottom of the offshore trench is more than 40,000 feet. And the length of the undersea troughs is no less remarkable than their depth: some are 2,000 miles long.

These great gashes in the sea floor are so unlike anything on land that they are difficult for us as land animals to visualize. It is hard to grasp the reality of a chasm so deep that seven Grand Canyons could be piled on one another in it, and so long that it would extend from New York to Kansas City. Yet these are the dimensions of the Tonga-Kermadec Trench.

The size and peculiar shape of the Pacific trenches stir our sense of wonder. What implacable forces could have caused such large-scale distortions of the sea floor? Why are they so narrow, so long and so deep? What has become of the displaced material? Are they young or old, and what is the significance of the fact that they lie along the Pacific "ring of fire"—the zone of active volcanoes and violent earthquakes that encircles the vast ocean?

Although the trenches are still only sketchily explored, some tentative answers to these questions can be gleaned from the information already obtained. We can take the Tonga-Kermadec Trench as a typical example.

The Trench lies on a long, nearly straight, north-south line east of the Tonga and Kermadec archipelagoes. At its northern end it has a slight hook. It begins there as a gentle, spoon-shaped depression, runs southeasterly between Tonga and Samoa, then turns and deepens, strikes south for 1,200 miles and finally shoals and disappears at a point



TONGA TRENCH would appear as in the upper drawing if viewed northward from a point in the central Tonga Islands, and if vertical distances were exaggerated by a

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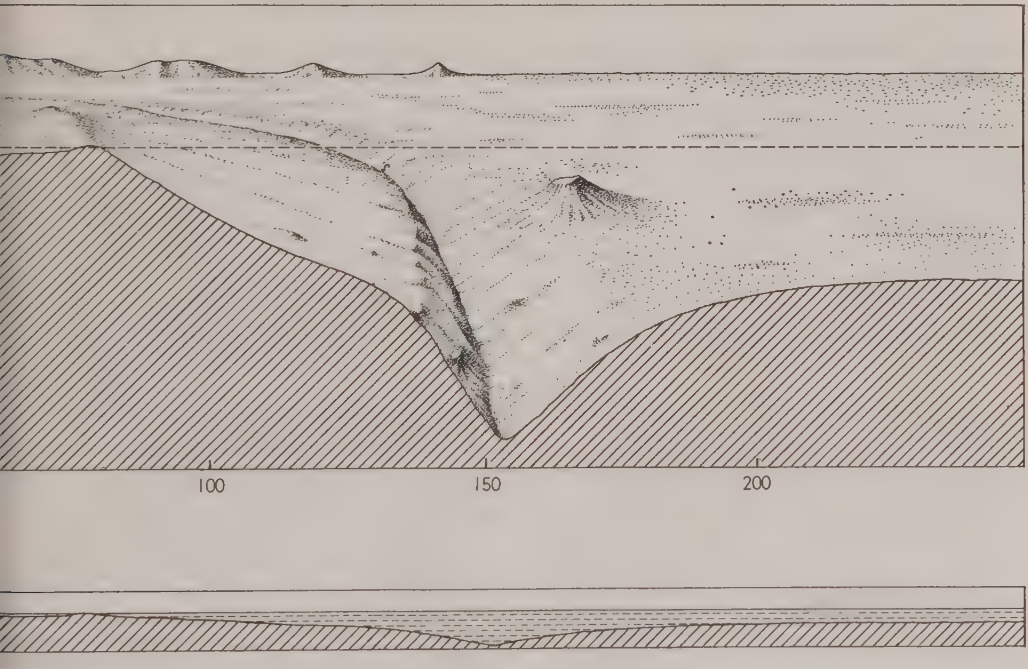
north of New Zealand. In its deepest central portion the Trench is very narrow—no more than five miles wide. The chasm is V-shaped, but the arm of the V on the island side is considerably steeper than on the seaward side: on the landward western wall the slopes average from 16 to 30 per cent—*i.e.*, in places they are steeper than the 24-per-cent-average slope of the sides of the Grand Canyon at Bright Angel. In longitudinal section the Trench consists of deep depressions separated by saddles; it looks like beads on a string, or peaks and saddles on an upside-down mountain range.

The islands on the western lip of the Trench appear to be part of the same crustal structure. They lie in two lines on a thousand-mile-long ridge atop the Trench's western slope. The islands of the Polynesian kingdom of Tonga are capped with limestones, laid down in shallow water during the last era of geologic time. These islands rest on broad shelves of drowned coral, 180 to 360 feet deep, and they rise in a series of terraces to a few hundred feet above sea level. West of the limestone islands, separated from them by a shallow trough, is a chain of submarine volcanoes and high volcanic islands. The volcanoes are explosive, rather than of the quiet Hawaiian variety. They have contributed great quantities of ash and cinders to the surrounding sea floor. Five of the island volcanoes have erupted during the last hundred years, and the danger of further explosions has forced the government of Tonga to evacuate the inhabitants. There are also active volcanoes below the sea surface. One of them, Falcon Bank, rises several hundred feet above the sea during an eruption; indeed, this bank is commonly called Falcon Island. After each eruption waves quickly erode the erupted lava, and within a few years the volcano is submerged again.

The floor of the Tonga-Kermadec Trench is rocky and seems to be nearly bare of sediments. During the Scripps Institution *Capricorn* expedition of 1952-1953, a core barrel with a heavy lead weight, which because of difficulties with the winch was dragged along the sea floor for several hours before it could be raised, came up badly battered by the bottom rocks. The heavy steel bail holding the instrument had been bent, and the lead weight looked as if it had been beaten with a hammer and chisel. Small fragments of black volcanic rock were embedded in the lead.

On the seaward slope of the Trench a single volcanic cone rises smoothly 27,000 feet, to within 1,200 feet of the sea surface. Just below its summit is a broad flat bench, tilted to the westward. Further study of this great cone, one of the highest mountains on earth, might tell us much about the history of the trench. Almost certainly the flat bench was cut by waves when the topmost part of the peak was above sea level. If



factor of 10 in comparison with horizontal. (In the lower drawing the cross section is shown without vertical exaggeration.) The exposed land mass in the left foreground is the island of Kao, a dormant volcano. In the distance are the Samoan Islands. The flat-topped seamount on the eastern slope of the trench is one of the highest mountains in the world. Its summit, which is tilted down toward the west about one degree, was probably worn flat by wave action when trench was shallower and mountain above water.

shallow-water fossils could be recovered from the summit, we could fix the time when submergence occurred, and perhaps when the bench began to be tilted. This in turn might give us information about the rate of downward bending of the trench floor.

The Tonga Trench, as we have said, is typical of the great trenches in the Pacific. Some of the other giant furrows are the Aleutian, Kurile, Japan, Marianas, Philippine and Java Trenches on the northern and western sides and the Acapulco and Peru-Chile Trenches on the eastern side of the ocean. It is a remarkable and probably significant fact that the deepest trenches all have about the same maximum depth. The record sounding so far was one estimated to be somewhere between 35,290 and 35,640 feet, made in the trench southeast of the Mariana Islands. Appropriately enough this depth was measured by H.M.S. *Challenger*, the modern namesake of the famous ship whose voyage around the world in the 1870s marks the beginning of modern oceanography [see "The Voyage of the *Challenger*," by Herbert S. Bailey, Jr.; Scientific American, May, 1953]. The original *Challenger* actually discovered the Marianas depression, and for many years it was known as the Challenger Deep.

All the deep trenches seem to be generally V-shaped in cross section, although some are slightly flattened at the very bottom; in the Japan and Philippine trenches this flat portion is two to 10 miles wide. Some shallower trenches and trenchlike depressions are U-shaped, with extremely flat bottoms over broad areas, as if they had been partly filled with sediments. If the V-shaped trenches contain any sediments, the layer cannot be more than a few hundred feet thick.

Direct exploration of the trenches is most difficult. Their great depth and extreme narrowness present formidable obstacles. To lower a dredge or other heavy sampling apparatus to the bottom of the deeper trenches, the ship needs a tapered wire rope of the strongest steel and a powerful, specially designed winch. Only three such winches exist today. One was built for the Swedish *Albatross* Expedition of 1948-49 and was later used on the Danish *Galathea* Expedition of 1950-52; another is installed on the Scripps Institution's research vessel *Spencer F. Baird*; the third is on the U.S.S.R. research ship *Vitiaz*. The winch drum on the *Baird* carries 40,000 feet of wire rope. When this wire was paid out in the Tonga Trench with a heavy core barrel on the end, the strain at deck level was 12 tons.

A single lowering of a dredge or core barrel takes many hours. It is complicated by the problem of keeping a small ship in position in a rolling sea, often under the influence of strong and unpredictable currents and shifting winds. The hazards of fouling the wire or of machinery breakdown under the heavy strain are always present, with the possible loss of the precious cable. Such a loss would be crippling, and much of the investment in time and effort required to send a scientific ship to a remote part of the world would also be lost.

If sounding and sampling of the bottom are difficult, drilling to find what lies beneath the bottom of the trenches is quite impossible, with present techniques. For such explorations we must depend on indirect methods—studies of earthquake waves, measurements of gravity anomalies, the flow of heat through the crust and the magnetic properties of the buried rocks.

The zone of trenches is the scene of our planet's most intense earthquake activity. Nearly all the major earthquakes, especially those originating at great depths, occur in this zone. The deepest-focus earthquakes are associated with the deepest and steepest trenches. This strongly suggests that the seat of the trench-producing forces lies far below the earth's surface.

The earthquakes may, indeed, be responsible for the fact that a line of explosive volcanoes parallels the trenches. Some investigators have proposed that the heat produced near the focus of an earthquake melts the surrounding rocks, and that the melted material rises and is eventually ejected by the volcanoes.

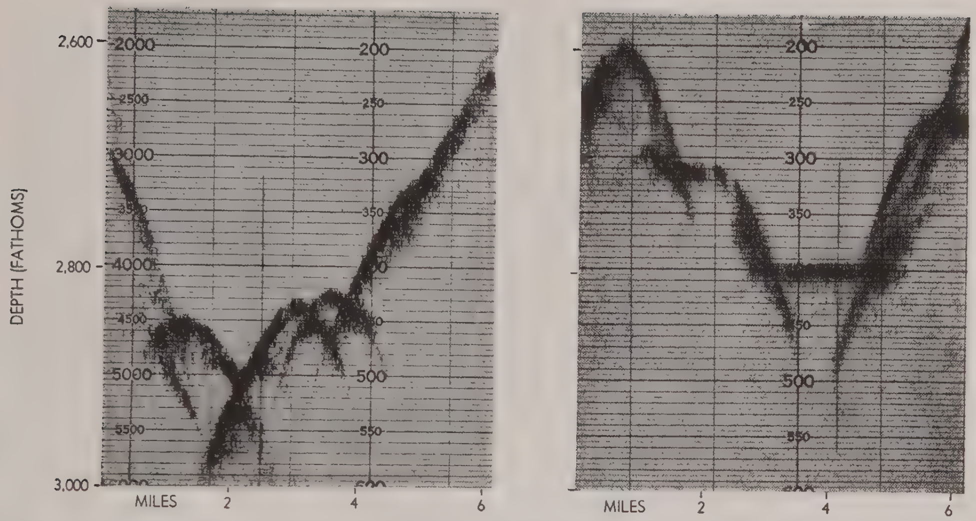
Seismic refraction studies give us another clue to the nature of the crust under the trenches. These investigations have shown that beneath the trenches (Tonga and others) the outer crust is less than one third as thick as under the continents. We therefore arrive at the important conclusion that the crustal structure under the trenches is oceanic and not continental.

The most striking phenomenon associated with the trenches is a deficiency in gravity. The force of gravity depends on the mass of matter between the surface and some great depth in the earth. In general this force at any given latitude is about the same in ocean basins as in the continents, despite the fact that the volume of rock under a continental area is greater than under an equal area of the ocean. Evidently the continents "float" high above the deep sea floor, like rafts of light material in a heavier medium. Within the continents themselves, there is usually little difference in gravity between high mountains and low plains, and it is commonly supposed that the mountains are underlain by a larger thickness of light material than the plains. This state of the earth's crust is called isostatic equilibrium.

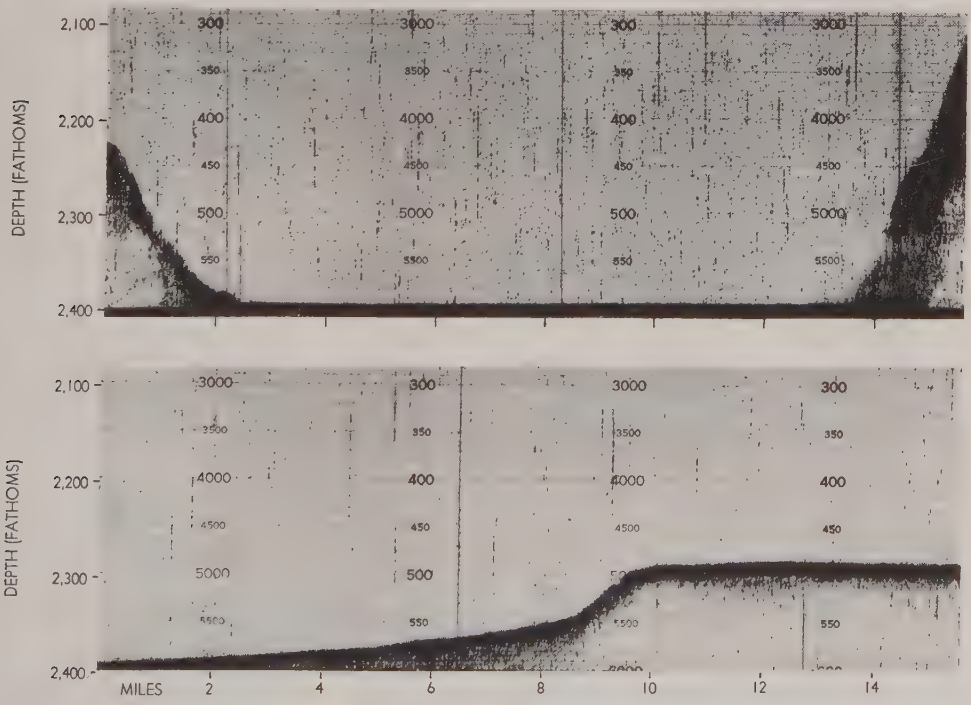
Measurements of gravity near trenches show pronounced departures from the expected values. These gravity anomalies are among the largest found on earth. It is clear that isostatic equilibrium does not exist near the trenches. The trench-producing forces must be acting against the force of gravity to pull the crust under the trenches downward!

What may these forces be? Here studies of heat flow in the crust suggest a possible answer. It has long been known that there is a small, steady flow of heat from the earth's depths outward toward the surface. Most of this heat is generated by the disintegration of radioactive elements in the crust and the mantle just beneath the crust. Near the surface of the earth the heat is transported outward principally by conduction, but at greater depths there may be a slow upward movement of the hot rock itself, carrying heat toward the surface. If rock at these depths moves upward in some regions of the earth, there must be other regions where cold rock moves downward. This movement would reduce the outward flow of heat. Now measurements near the floor of the Acapulco Trench show that the flow of heat there is less than half the average for the earth's surface (the average being about 250 calories per year per square inch of surface). So it may be that relatively cool rocks are slowly moving downward under the trench. Such a downward flow would tend to drag the crust down with it and may well account for the formation of the trench. If this process is occurring, the earth's mantle should be cooler under the trench than elsewhere. Magnetic measurements suggest that this is in fact the case, but they are too few so far to be conclusive.

Speculating from what we know, we may imagine that a trench has the following life history. Forces deep within the earth cause a foundering of the sea floor, forming a V-shaped trench. The depth stabilizes at about 35,000 feet, but crustal material, including sediments, may continue to be dragged downward into the earth. This is suggested by the



ACAPULCO TRENCH is revealed in cross section by echo soundings. Near Acapulco (*left*), the bottom is V-shaped, with little sediment, and 2,930 fathoms deep. Near Manzanillo (*right*), it is flat at 2,795 fathoms. Numbers on the records do not represent fathoms.



CEDROS TROUGH, a short trench off the coast of Lower California, is traced in cross section by the upper echo-sounding and longitudinally by the lower. The bottom is flat at 2,395 fathoms and measures 11 miles across at the point where measurement was made.

fact that the deepest trenches contain virtually no sediments, although they are natural sediment traps. During this stage in the trench's history there is violent volcanic and earthquake activity.

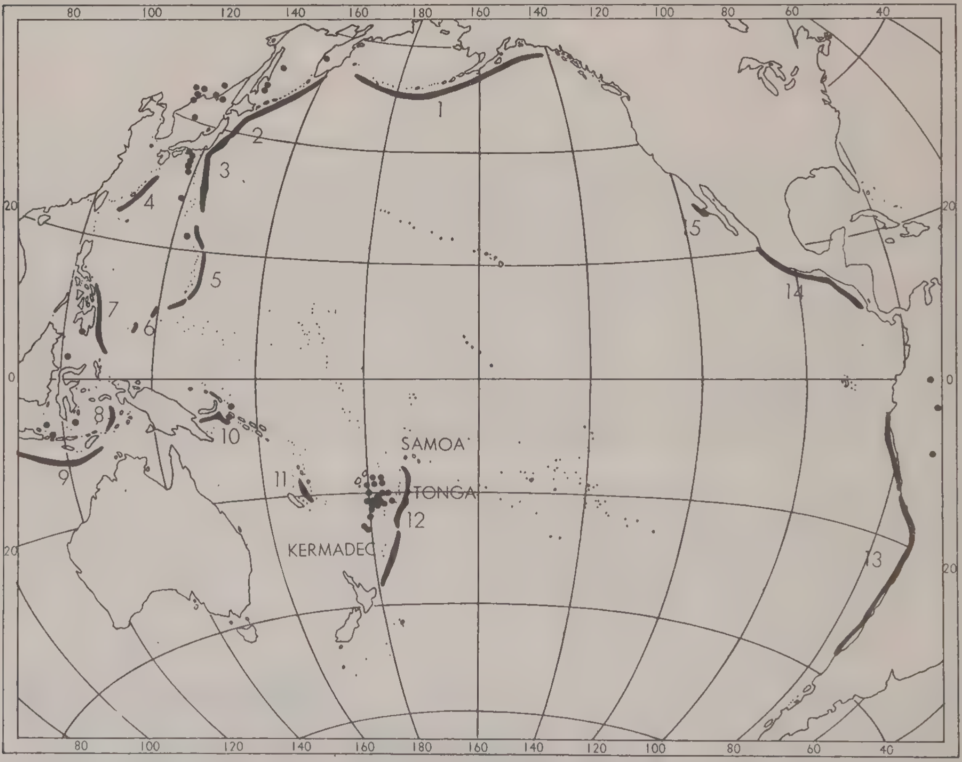
In a later stage the internal forces pulling or squeezing the crust downward under the trench become less active, and the trench begins to fill up with sediments. It acquires a flat bottom and a U shape as the accumulating sediments cover the topographic irregularities. The sediments may eventually pile up so high that the top of the pile rises above the sea, forming islands, when isostatic equilibrium is finally restored. The topmost sediments will be rock of the kind that is deposited in shallow water, like the limestones of Tonga and the Marianas.

Another process also may come into play if a thick layer of sediments accumulates. Because of their lower heat conductivity, the sediments would form an insulating blanket along the former trench. This would block the heat flow from the interior and cause a temperature rise which would partly melt the deep rocks. The melted material might then move upward and transform the heavy existing rock and the lower part of the sedimentary layer into light, granite-like rock. The thickness of the crust therefore should increase.

Some geophysicists have suggested that it was by such a sequence of events, occurring repeatedly during the geologic past, that the continents grew, at the expense of the ocean basins. The question then arises: Where on the continents are the ancient, filled-in trenches?

One naturally thinks at once of the long, narrow structures, called geosynclines, where sediments piled up and mountain ranges developed by compression and folding. Were some geosynclines originally deep trenches such as now exist on the sea floor? It has usually been thought that this is not so, because most of the sediments in geosynclines appear to have been laid down in shallow water rather than in deep trenches. However, this appearance may in some cases be an illusion. Sediment samples collected from even the deepest trenches resemble in many ways deposits laid down in shallow water.

It is true that the sedimentary rocks in geosynclines contain no recognizable fossils of deep-sea animals. But trenches have little life that could leave a distinctive record. The depths of a trench are completely dark, except for the fee-



RING OF TRENCHES around the central basin of the Pacific is shown in color. The colored dots represent deep centers of earthquake activity. Numbered serially are: Aleutian Trench (1), Kurile Trench (2), Japan Trench (3), Nansei Shoto Trench (4), Marianas Trench (5), Palau Trench (6), Philippine Trench (7), Weber Trough (8), Java Trough (9), New Britain Trench (10), New Hebrides Trench (11), Tonga-Kermadec Trench (12), Peru-Chile Trench (13), Acapulco-Guatemala Trench (14), Cedros Trough (15).

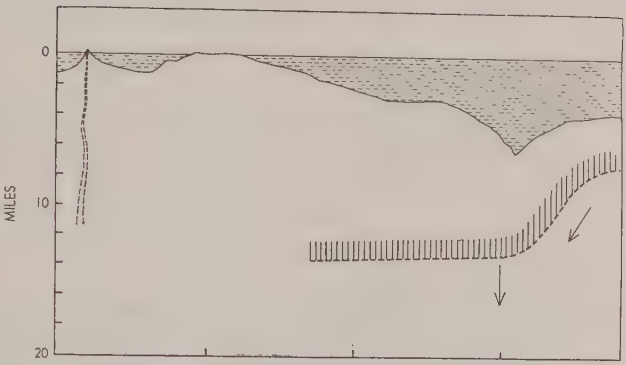
ble and flickering light produced by luminous organisms, and no plants can live there. The animals and bacteria of the abyss must gain their sparse food supply from plant and animal remains settling slowly from the upper layers of the sea. The waters are very cold: about 36.5 degrees Fahrenheit now, though they may have been some 20 degrees warmer in the geologic past. The pressure at the bottom of a trench is, of course, enormous—more than eight tons per square inch.

The Danish *Galathea* Expedition several years ago dredged up a few animals from the floors of trenches more than 30,000 feet deep. The principal animals recovered were sea cucumbers and a type of sea anemone, neither of which would be likely to leave distinctive fossils. Some worms, clams and crustaceans also were obtained, together with beautiful glass sponges.

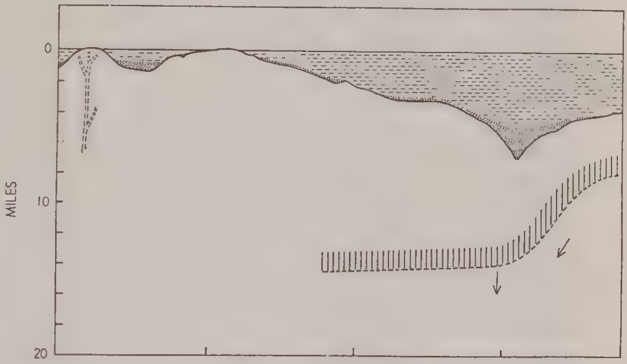
Materials which are usually supposed to be deposited only in shallow water have actually been found on the floor of some of the deep trenches. The *Galathea* recovered fine gray sand, pebbles, cobbles and land-plant debris from the floor of the Philippine Trench. The Lamont Geological Observatory of Columbia University found, in cores from the Puerto Rico Trough, the skeletons of plants and animals that live only at shallow depths. In the flat-bottomed northern part of the Acapulco Trench one core contained soft black mud, high in organic debris and stinking of hydrogen sulfide, while in other cores layers of gray, green and brownish sand and silt were interbedded with charred woody fragments and fine green mud.

However, it is clear that some geosynclines, notably those along what are now the Appalachian Mountains, could not have been deep sea trenches, for they contain deposits from marshes and flood plains interbedded with marine sediments, and therefore the deposits must have been laid down in shallow water.

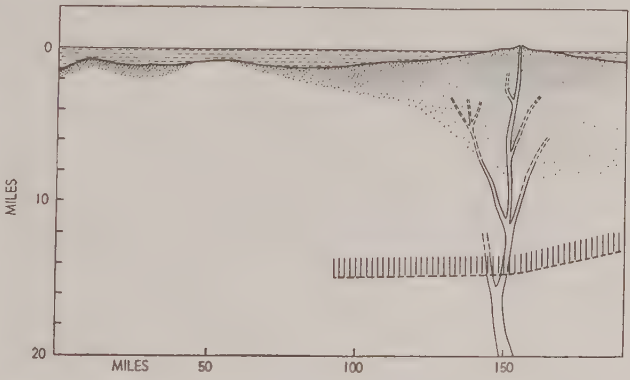
The question remains: Where are the trenches of yesteryear? Are we living in an exceptional geologic era; are the apparently young trenches of the present day unusual formations that have had no counterparts during most of geologic time? Such a speculation would be repugnant to many geologists, because it would be difficult to reconcile with the doctrine that the present is the key to the past. We must continue to search for ancient trenches—on the deep-sea floor, in the marginal shallow water areas and on the continents themselves.



POSSIBLE LIFE HISTORY of a trench is outlined in the three diagrams on this page. Here a force deep within the earth pulls down the floor of the ocean to form a V-shaped trench.



SEDIMENT COLLECTS in the bottom of the trench during the second stage, when the deep force weakens and relaxes its downward pull. Bottom is now flat and V changes to U.



SEDIMENT BUILDS UP and, with isostatic adjustment of the crust, rises above the surface of the sea. Deep molten rock rises through the sediment and is released by volcanoes.

Contribution from Scripps Institution of Oceanography, New Series No. 812.

A DEPTH TELERECORDING UNIT FOR MARINE BIOLOGY[1]

By

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JAMES M. SNODGRASS AND ROBERT F. DEVEREUX
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A serious obstacle to critical examination of stratification and diurnal migration of plankton has been the lack of instruments that enable the biologist to ascertain accurately the depth of his collecting net at the time of opening, fishing and closing. This lack has been felt particularly by those interested in the biology of organisms in the sonic scattering layer (D.S.L.). Since the vertical migration of these animals starts rather suddenly, proceeds rapidly, and extends through a great distance, precise determination of the depth at which the net fishes is essential.

Much justifiable criticism has been levelled at earlier investigations in which the fishing depth has been inferred from length of wire out and wire angle at the surface. These objections have been met in part by use of a time-depth recorder which has shown the fishing depth *after* the tow has been completed. Frequently it has been discovered, too late, that the net was nowhere near the calculated depth and that time had been wasted. In addition, mechanical failure of the recorder is not detected until the instrument is brought to the surface. Thus such recorders as have been in use have merely revealed the depth at which the net was fishing and have not provided data for setting and maintaining the nets at the desired depth. To meet the need for more accurate observation and operation, an instrument has been developed which records on deck with great accuracy the depth at which the collecting net is being towed.

This Depth Telerecording Unit has been used successfully in controlling the depth of a one-meter nylon plankton net at all times within a range of 3 m during a horizontal tow, even when more than 450 m of wire is out. The biologist controls the depth, as indicated on deck, by careful adjustment of ship speed and amount of wire out.

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[1] Contributions from the Scripps Institution of Oceanography, New Series, No. 813. This work was supported in part by funds from the Office of Naval Research and from the Bureau of Ships, U. S. Navy.

Reprint from SEARS FOUND. JOURN. MAR. RES

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(1015)

With a modified Leavitt mechanism,[2] the collecting net was opened and closed at a known depth.

Frequent use of this instrument together with the wire-angle method of ascertaining depth should provide data which will lead to greater accuracy for the latter method or which will, at least, describe the limits of accuracy for that method.

The Depth Telerecording Unit has been fabricated at Scripps Institution both as a separate unit and as a built-in accessory to other instruments. The instrument, which is relatively simple and inexpensive to build,[3] provides dependable accuracy as well as sufficient ruggedness to ensure long life expectancy.

The instrument consists essentially of a 10,000 ohm Giannini Microtorque potentiometer actuated by the Bourdon mechanism of a James P. Marsh 4-inch Master Gage, type 100, 0–1500 psi, 0.5% accuracy. These and other components of the instrument are protected from ambient hydrostatic pressure by a thick-walled pressure-tight steel chamber. The Bourdon element is completely filled with silicone oil to prevent corrosion by sea water. Pressure (depth) is measured through an opening in the pressure-tight chamber. This opening is sealed by a Sylphon 1-ply brass compliant bellows, approximately 2 cm in length and in diameter, to prevent loss of silicone or intrusion of air or water.

The 10,000 ohm potentiometer, selected because it produces only small battery drain, permits the use of mercury cells in the circuit. The result is essentially constant voltage for relatively long periods of time, thus making frequent battery changes or depth calibration unnecessary. The interior of the instrument, showing the method of connecting the Bourdon mechanism to the potentiometer, is shown in Fig. 1. Rotation of the shafts of the Bourdon and of the potentiometer is limited to 270°.

In assembling this instrument, proper adjustment of the flexible coupling between the Bourdon mechanism and the Microtorque potentiometer is essential. The coupling, nothing more than a short length of neoprene O-ring stock, is drilled at the ends for a press fit over the end of each shaft. However, in order to realize the low-torque characteristics of the potentiometer there must be no end thrust on the shaft. Adjustment may be made by eye because there is ample axial clearance. The actual adjustment is not critical so

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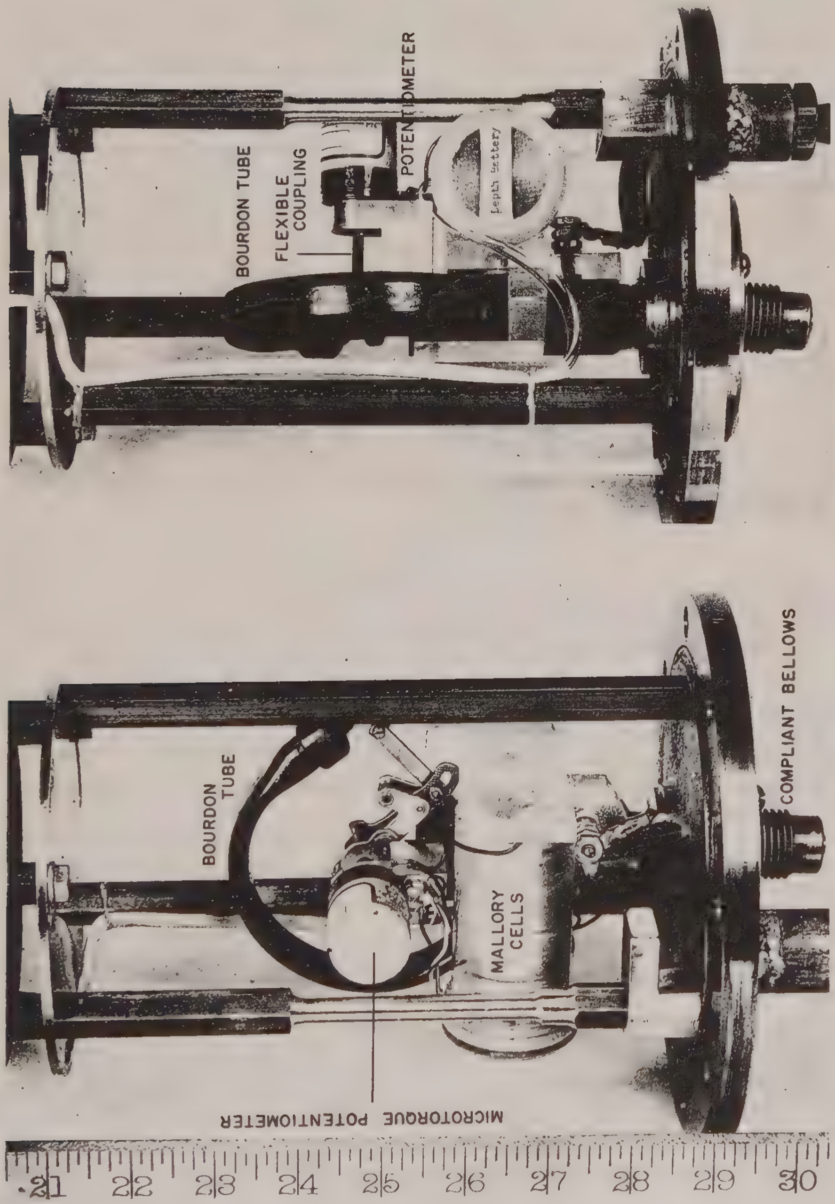
[2] Leavitt, B. B., 1935, A quantitative study of the vertical distribution of the larger zooplankton in deep water. Biol. Bull. Woods Hole, *68:* 115–130.

[3] In the United States, cost of components and materials, exclusive of cable and recorder, is approximately $100. Shop time required to build the instrument is approximately 30 hours.


BOURDON TUBE
FLEXIBLE COUPLING
POTENTIOMETER
Depth battery
BOURDON TUBE
MALLORY CELLS
COMPLIANT BELLOWS
MICROTORQUE POTENTIOMETER
21
22
23
24
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26
27
28
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Figure 1. Interior views of Depth Telerecording Unit. 1V5 vacuum tube not shown. Scale in inches.

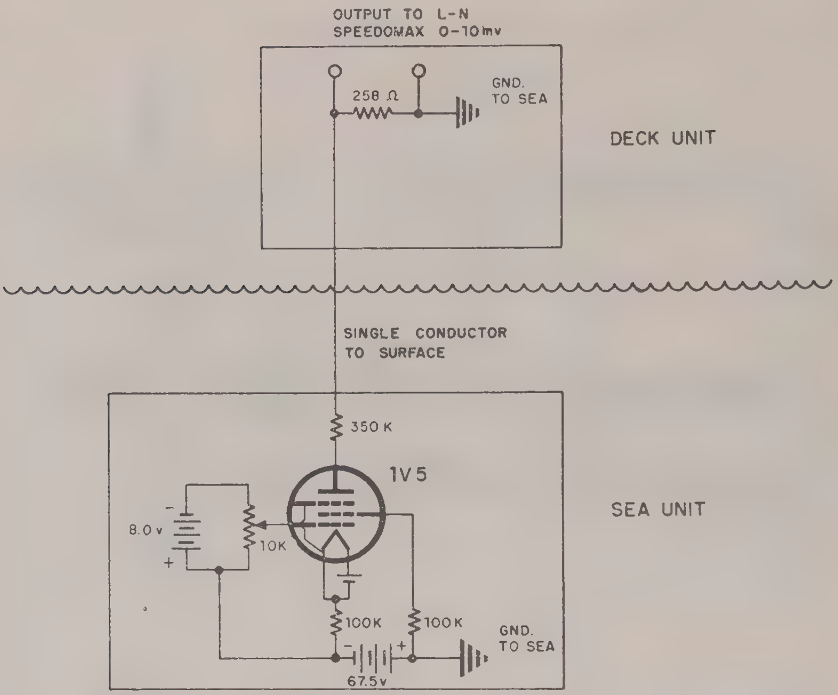
OUTPUT TO L-N
SPEEDOMAX 0-10 mv
258 Ω
GND. TO SEA
DECK UNIT
SINGLE CONDUCTOR
TO SURFACE
350 K
1V5
SEA UNIT
8.0 v
10K
100K
100K
GND. TO SEA
67.5 v

Figure 2. Typical circuit for use with single insulated conductor to surface.

long as the shaft is nearly midway between the thrust limits. Also, it has been found necessary to increase tension of the Bourdon mechanism hair spring beyond that established at the factory. Without these two adjustments the instrument responds poorly to changes in pressure (depth).

The Unit is accurate to within less than 0.5% of actual depth in the range of 0–1000 m. Experiment has shown that it is little affected by temperature. A change of 20° C. (27° to 7°) produced a change in response to pressure (depth) that was substantially less than 0.25% (the temperature coefficient is less than 0.012). At a depth of 500 m the error would be less than 1 m.

The instrument may be used as an indicating or recording device. Depending on the circuitry employed, it is capable of operating along single or double conductor cable. A typical circuit is shown in Fig. 2. Here the instrument includes a 1V5 miniature vacuum tube which permits telerecording of data along a single-conductor insulated cable to a Leeds-Northrup Speedomax recorder on deck.

The cable used with this instrument is polyethylene-jacketed steel wire having a breaking strength of more than 2700 pounds (approximately 100 kg). Since this cable is nearly weightless in water by virtue of the buoyancy of the tough plastic jacket, a substantial fraction of the 2700 pounds may be used to support instruments and tow nets. The investigator should use whatever safety factor he considers desirable. There are, of course, some inertia loads that result from ship motion, etc. A simple accumulator, made from several loops of heavy shock cord and installed between the meter-counting sheave and the boom, has been used with this cable to reduce inertia loads experienced on small, active vessels.

ECOLOGY OF LIVING BENTHONIC FORAMINIFERA TODOS SANTOS BAY, BAJA, CALIFORNIA

BY

WILLIAM R. WALTON

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Reprinted from
Journal of Paleontology
Vol. 29, No. 6, November, 1955

JOURNAL OF PALEONTOLOGY, VOL. 29, NO. 6, PP. 952–1018, PLS. 99–104, 24 TEXT-FIGS., NOVEMBER 1955

ECOLOGY OF LIVING BENTHONIC FORAMINIFERA, TODOS SANTOS BAY, BAJA CALIFORNIA[1]

WILLIAM R. WALTON[2]
Scripps Institution of Oceanography, La Jolla, California

ABSTRACT—Two hundred and fifteen sediment samples were collected in Todos Santos Bay, Mexico, and vicinity during eight cruises on February 5, March 3, April 24, June 4, July 16, August 28, October 9, and November 10, 1952. Thirty-three sediment samples were collected in the Estero de Punta Banda. Bathythermograms from 429 stations, salinity measurements from selected stations, and water and sediment temperature observations aid in defining the physical and chemical environments.

Living benthonic foraminiferal populations have been analyzed from 215 sediment samples, dead populations have been analyzed from 110 samples, and sediment size analyses have been made on 70 samples.

The characteristics of the sediments indicate that "relict" sediments which represent a previous environment are present in the bay along with the modern sediments representing the present environment. The occurrence of non-living shallow-water species in areas of "relict" sediments suggests that the associated foraminiferal faunas are relict, at least in part.

Four geographic assemblages (Outer Bay, Middle Bay, Inner Bay, and Marginal Bay facies) and four depth facies (less than 30 fathoms, 30–50 fathoms, 50–100 fathoms, and deeper than 350–400 fathoms) have been recognized from the distributions and abundances of the living benthonic Foraminifera. These facies suggest that variations in sediment type, food or feeding habits, etc., may limit the distribution of benthonic Foraminifera, in addition to depth and/or temperature variations.

Maximum abundances of living benthonic Foraminifera have been found to occur during the late spring and summer months and apparently are associated with spring and summer flowering of phytoplankton and the seasonal temperature maximum during August. The maximum abundance occurs between 20 and 50 fathoms, and production estimates suggest that these depths apparently are 6 times as productive as depths between 350 and 400 fathoms.

Dead-population counts are valid in defining the composition and general distribution of benthonic foraminiferal faunas but are not indicative of the actual distributions or abundances of living faunas. The rate of accumulation of detrital sediments appears to be the most important single factor in determining the magnitude of dead populations. Living-to-dead ratios of benthonic Foraminifera appear to be good indices of relative rates of sedimentation.

The occurrence of middle Tertiary strata outcropping near the surface of the sediment on the continental shelf off Todos Santos Bay suggests that some of the nonliving deeper-water species occurring in surface sediments are reworked and do not represent the living foraminiferal faunas.

INTRODUCTION

THIS study was undertaken to investigate the distribution of living Foraminifera in Todos Santos Bay, Mexico, and their relationships to the environments in which they live. Sediment samples were collected during February, 1952, covering the entire Todos Santos Bay. Additional samples were collected along a single profile from shallow water to a depth of 600 fathoms to study seasonal variation at approximately six-week intervals for the remainder of the year. The purposes are: (1) to compare the living benthonic populations with the dead populations in various environments; (2) to compare the living and dead populations with the sediment type; (3) to attempt to relate the distribution of the living faunas with known physical and chemical factors; and (4) to investigate the rate of production and accumulation of foraminiferal tests.

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[1] Contribution No. 23, Marine Foraminifera Laboratory. Contribution, n.s., No. 814, Scripps Institution of Oceanography.

[2] Now employed by Gulf Research & Development Company, Houston, Texas.

(1022)

ACKNOWLEDGMENTS

The field work was done on the research vessels of the Scripps Institution of Oceanography of the University of California. Laboratory facilities were furnished by the Marine Forminifera Laboratory and the Division of Geology of the same institution: The laboratory work was supported in part by the Office of Naval Research, under Contract No.-23301. The study was supervised by Fred B. Phleger, and in addition, M. N. Bramlette, J. Wyatt Durham, U. S. Grant IV, N. W. Rakestraw, and Francis P. Shepard critically read the manuscript and gave valuable suggestions. Jean Peirson drafted many of the illustrations. Ann Walton retouched the photographs and assembled the plates. The writer is indebted to the following people for assistance in the collection of the samples and field data: Stockton Andrews, Robert Bieri, John S. Bradshaw, Theodore Chamberlain, Neville Curtis, R. L. Fisher, Theodor S. Geisel, Richard Mills, James Moriarty, Kenneth S. Norris, Charles F. Phleger, Walter Scott, P. C. Scruton, and Maxwell Silverman. D. L. Inman critically read the manuscript and assisted in the interpretation of the sediments and statistical presentation of the data.

DESCRIPTION OF THE AREA

GEOGRAPHY

Todos Santos Bay lies about 60 nautical miles southeast of San Diego on the coast of Baja California, Mexico; it extends from Lat. 31°40′ N. to 31°56′ N., and from Long. 116°36′ W. to 116°50′ W. It is a large, open bay (Text-fig. 1) with a total area of approximately 90 square miles. The bay is bounded on the south and west by the rocky, mountainous Punta Banda and the Todos Santos Islands, and on the north by the mainland coast of Baja California. The inner boundary of the bay is low and is characterized by long sandy beaches and low beach dunes.

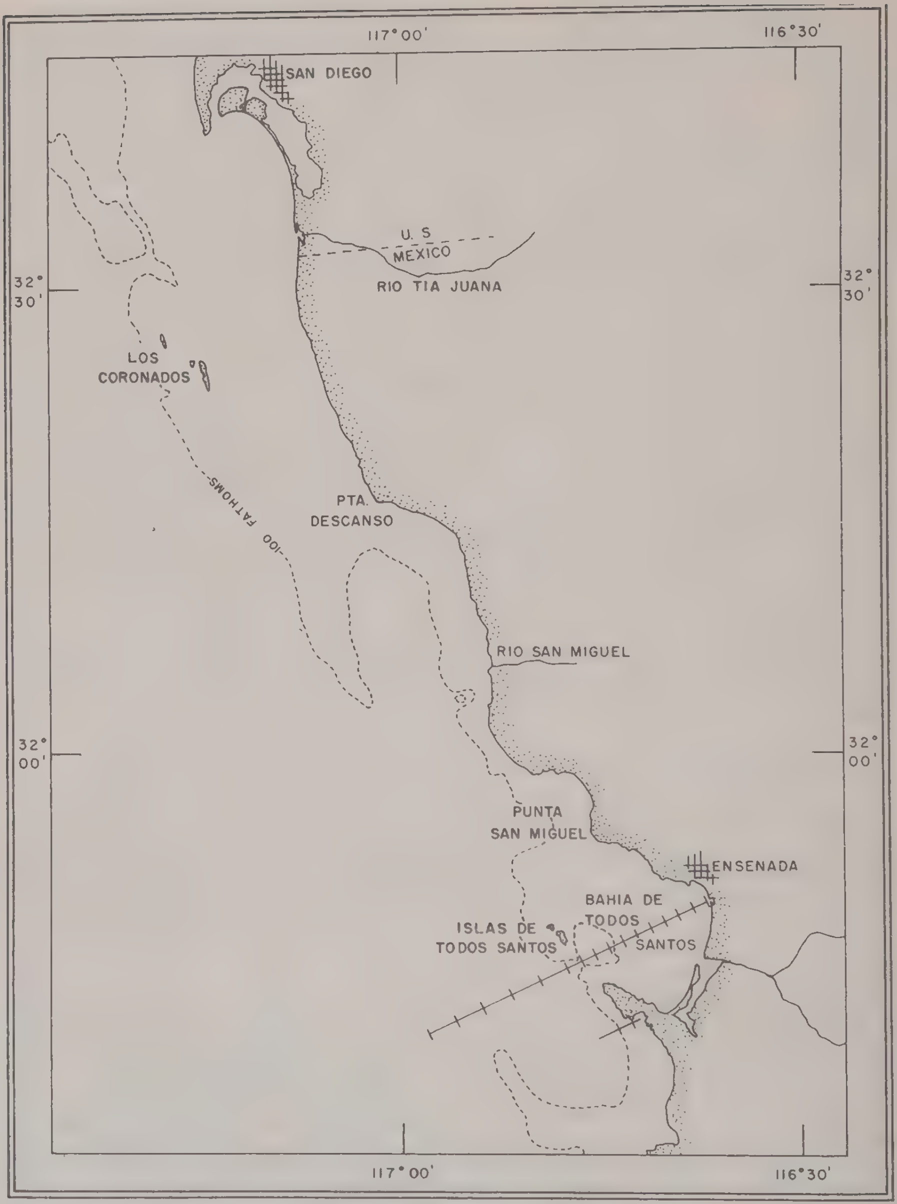
A large marine marsh, Estero de Punta Banda, is separated from the bay by a low sand spit which extends from Punta Banda toward the northeast for a distance of approximately 4 miles. It is characterized by its L-shaped main channel and poorly-developed marsh on the back side of the sand spit (Text-fig. 2). The channel is relatively shallow, not exceeding a depth of 20 feet in the deepest portion. The marsh on the west side of the Estero de Punta Banda is covered by marsh grasses. However, there is no thick accumulation of peat, and the marsh is cut along its length by sinuous tidal channels. There is no continuous fresh-water drainage into the channels, but during times of heavy rains considerable fresh water flows in through the normally dry river beds near the mouth of the estero and along the base of Punta Banda.

The south shore of Todos Santos Bay, along Punta Banda, is rocky and precipitous. The north shore of the bay also is rugged with the exception of isolated pocket beaches. The two Todos Santos Islands lie about 3.5 nautical miles northwest of Punta Banda. The south island, which is the larger, is approximately 2.5 miles long and 1.5 miles wide at the widest point. It is high (with the highest peak at approximately 300 ft. elevation), has rocky cliffs, and is inaccessible except for a few pocket beaches on the lee side. The north island is separated from the south island by a narrow, shallow channel. The north island is low and flat, and is approximately 1¼ miles long and ½ mile wide.

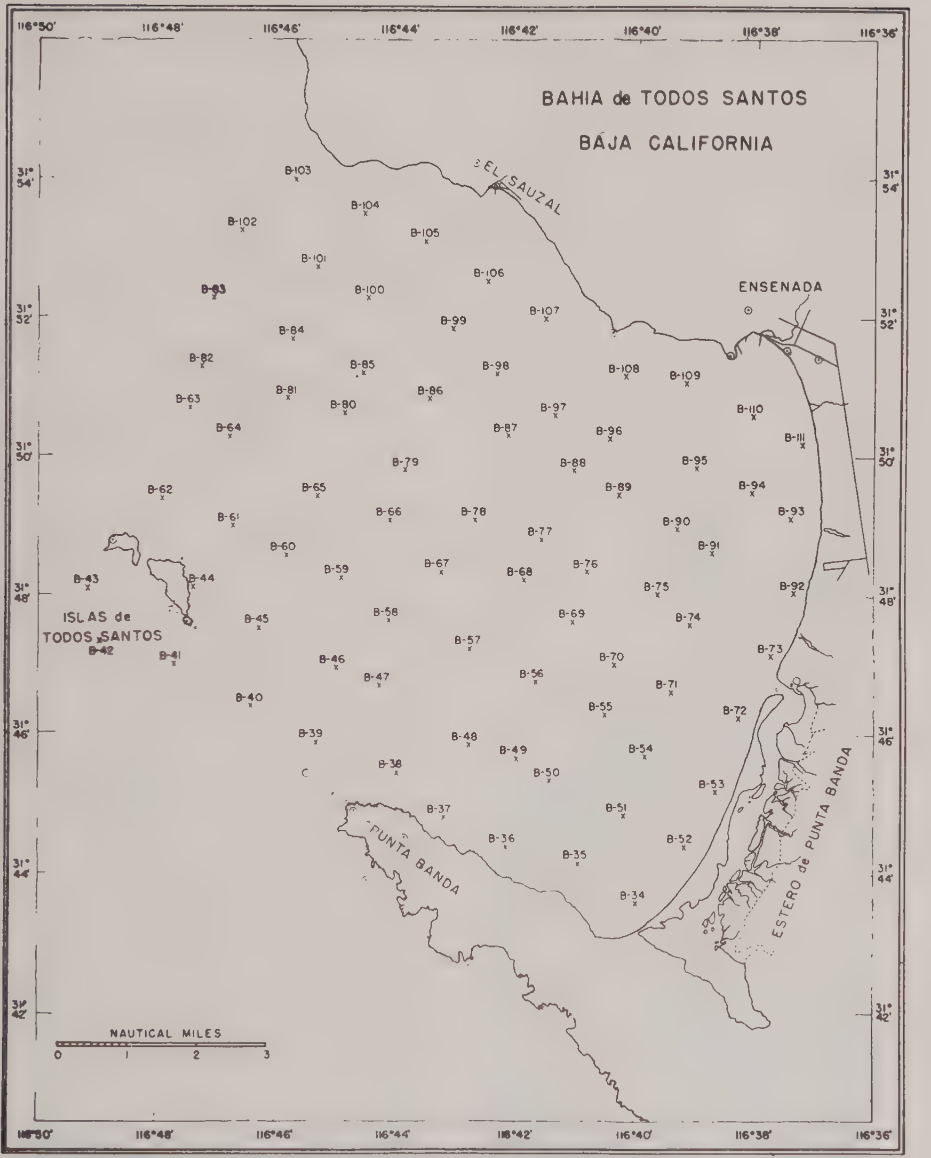
SUBMARINE TOPOGRAPHY

The water depths over most of the bay are less than 40 fathoms (Text-fig. 3). Exceptions are the deep channel between Punta Banda and the Todos Santos Islands (which is 215 fathoms deep) and the depression inside the line between the islands and Punta Banda (which is 150 fathoms deep). This depression has a moderately steep slope on the bay side but is bounded by slopes up to 30° on the side near the islands and Punta Banda. The channel is steep-sided and narrow, being only a few hundred yards wide at its deepest portion.

Nelson (1921, p. 85) reported a continuous submarine ridge connecting Punta Banda and the south Todos Santos Island. He also reported faunal and floral similarities between Punta Banda and the islands and concluded that they were once continuous. It appears that Punta Banda at some time in the past was continuous across the present deep trough and was connected


117°00'
116°30'
SAN DIEGO
U. S
MEXICO
RIO TIA JUANA
32° 30'
LOS CORONADOS
PTA. DESCANSO
100 FATHOMS
RIO SAN MIGUEL
32° 00'
PUNTA SAN MIGUEL
ENSENADA
BAHIA DE TODOS SANTOS
ISLAS DE TODOS SANTOS

TEXT-FIG. *1*—Location of area and seasonal traverse.


BAHIA de TODOS SANTOS
BAJA CALIFORNIA
EL SAUZAL
ENSENADA
ISLAS de TODOS SANTOS
PUNTA BANDA
ESTERO de PUNTA BANDA
NAUTICAL MILES
0
1
2
3
116°50'
116°48'
116°46'
116°44'
116°42'
116°40'
116°38'
116°36'
31° 54'
31° 52'
31° 50'
31° 48'
31° 46'
31° 44'
31° 42'
B-103
B-104
B-102
B-105
B-101
B-106
B-83
B-100
B-107
B-99
B-84
B-82
B-85
B-98
B-108
B-109
B-81
B-86
B-63
B-80
B-97
B-110
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B-111
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B-49
B-54
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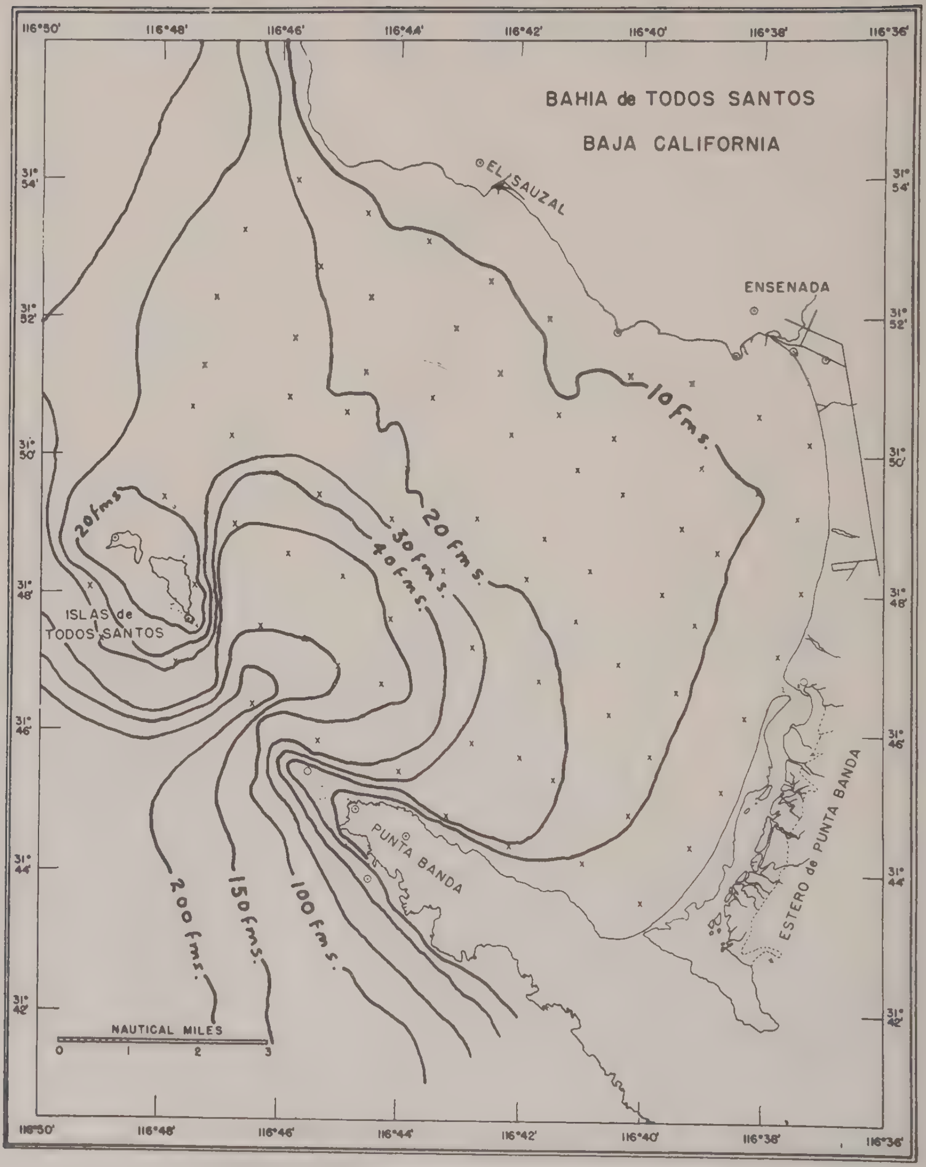
B-52
B-35
B-34

TEXT-FIG. 2—Locations of stations in Todos Santos Bay.


BAHIA de TODOS SANTOS
BAJA CALIFORNIA
EL SAUZAL
ENSENADA
ISLAS de TODOS SANTOS
PUNTA BANDA
ESTERO de PUNTA BANDA
10 fms.
20 fms.
30 fms.
40 fms.
100 fms.
150 fms.
200 fms.
NAUTICAL MILES
0
1
2
3
116°50'
116°48'
116°46'
116°44'
116°42'
116°40'
116°38'
116°36'
31° 54'
31° 52'
31° 50'
31° 48'
31° 46'
31° 44'
31° 42'

TEXT-FIG. 3—Bathymetric chart of Todos Santos Bay.

to the south Todos Santos Island. Numerous fathograms across the channel between Punta Banda and the islands show conclusively that there is no continuous ridge connecting them at the present time. Sharp steep ridges extend from the south island toward the southeast and from Punta Banda toward the northwest, but they slope steeply and terminate in a narrow trough-shaped channel. This deep channel heads into the depression just inside the islands and is well marked on the bathymetric chart (Text-fig. 3) by the 100-fathom contour.

The depression and the channel apparently are remnants of a submarine canyon. The more gentle inner slope of the depression appears to be a depositional slope in contrast to the steep structural and/or erosional slopes near the islands and off Punta Banda.

GEOLOGY OF SURROUNDING LAND

The geology of the area surrounding Todos Santos Bay is inadequately known. There are two exposures of sedimentary rocks in the area which have been examined: Upper Cretaceous sandstones, limestones, and conglomerates along the north side of Punta Banda and a thick wedge of sandstones and conglomerates on the north Todos Santos Island. Upper Miocene agglomerates, tuffs, and fresh-water sandstones have been reported on the mainland to the north of the bay (Beal, 1948, pl. 1), but have not been examined in the course of this study.

The Upper Cretaceous strata lie unconformably on the Cretaceous and pre-Cretaceous crystallines which constitute the mass of Punta Banda. They form precipitous cliffs which reach a height of 150 feet in some places. The top of these Cretaceous strata has been truncated by an old marine terrace and they are capped by alluvium. C. A. White (1885) first described the fauna from these strata and correlated them with the Chico group of California. Since this description, many new species have been added by Fairbanks (1893), Anderson & Hanna (1935, p. 7), and others, each concluding that these strata represent the Chico group of California. Beal (1948, p. 42) includes these strata in his Rosario formation along with the other Upper Cretaceous beds of Lower California.

The sedimentary strata along Punta Banda are not all equivalents of the fossiliferous strata described above. About midway along the Punta Banda exposures a fault separates the steeply-dipping sandstones and limestones of the Chico from horizontal strata of reddish fanglomerate-type deposits. These lie unconformably on the crystalline basement at the foot of the sea cliff and are non-fossiliferous. They consist of angular pebbles and cobbles in a matrix of fine- to medium-grained sandstones. These red beds appear in the Holderness well, near the mouth of the Tia Juana River, with a thickness of 269 feet. Similar red beds, 944 feet thick, occur beneath the well on Point Loma, California, drilled by the Borderland Exploration Company. According to Hertlein and Grant (1944, p. 39):

> ". . . these red beds may be a southern extension of the Trabuco formation in the Santa Ana Mountains, Orange County, Calif. . . . The red conglomerate resting on the diorite at Punta Banda, on the south shore of Todos Santos Bay, . . . may likewise represent the Trabuco formation. At that locality the fossiliferous Cretaceous is in fault contact with the red beds."

The sandstone and conglomerate exposures on the north Todos Santos Island were first reported by Lindgren (1888–89, p. 172). He correlated them with the Upper Cretaceous strata of Punta Banda. These exposures were examined and found to be non-fossiliferous. There appears to be no reason for correlating them with the fossiliferous sandstones and limestones of Punta Banda. Lithologically they are similar to the red fanglomerates but dip approximately 30° to the northwest. They are faulted against volcanic rocks at the south end of the island and are cut by numerous smaller faults along the length of the exposure. It is not possible to date these strata, but they appear to be the equivalents of the fanglomerates along Punta Banda. It is suggested that they may be near the distal end of the same alluvial fan. This suggestion is supported by their apparent structural position, by the fact that they are finer grained than the Punta Banda fanglomerates, and by the presence of sporadic mudcracks.

Beal (1948, pl. 1) shows extensive exposures of what he calls the Comondú formation, along the north shore of Todos

Santos Bay. These exposures have not been examined in the course of this study, but Beal states (op. cit., p. 74) that they contain "all volcanic rocks and terrestrial sediments of Tertiary age . . . ." He also states (op. cit., p. 74) that

> " . . . the bulk of the rocks so shown, however, are the product of a period of great volcanic activity, probably of Upper Miocene age . . . " "The formation is heterogeneous in composition and variegated in color. It includes large porphyritic and dense intrusives, rhyolite, andesite, and basaltic lava and tuffs, agglomerates, and mud flows, as well as conglomerates, sandstones, clays, and some limestones."

PREVIOUS STUDIES OF FORAMINIFERA

There has been no previous study of Foraminifera in the Todos Santos Bay area. The first detailed study of the ecology and depth zonations of Foraminifera off the coast of southern California was published by Natland (1933). He studied a series of samples extending from San Pedro Bay and across San Pedro Channel to Catalina Island. From these samples he was able to establish five faunal zones, as follows:

Zone I	Shallow, brackish-water lagoon (inter-tidal)
Zone II	Open ocean; depth range 14–125 ft.
Zone III	Depth range 125–900 ft.
Zone IV	Depth range 900–6,500 ft.
Zone V	Depth range 6,500–8,340 ft.

He suggests that temperature has a greater influence on the zonation of Foraminifera than depth.

Phleger (1951a) reported on a few foraminiferal samples off San Diego and recognized two general assemblages with the boundary between the two being at 100–200 fathoms. He also recognized shallow-water faunas which had been displaced down-slope into deeper water.

Butcher (1951) examined the Foraminifera of Coronado Bank and vicinity off San Diego. Four faunal facies were established; 130 m. to 260 m., 290 m. to 440 m. 490 m. to 550 m., and 730 m. to 810 m., with the major facies boundary at 390 m.–440 m. Temperature and salinity are considered by Butcher to be the most important ecological factors affecting these faunal facies.

Crouch (1952) studied the Foraminifera from cores taken in the deep basins off southern California. He was able to establish four biozones which are more closely correlated with temperatures than oxygen or salinity variations:

T4	Depth range 900–2,000 ft.
T5	Depth range 2,000–4,000 ft.
T6	Depth range 4,000–7,500 ft.
T7	Depth range approx. 7,500 ft.—?

Crouch found that the foraminiferal faunas were uniform from the sill depths to the bottom of the basins which correspond to the nearly constant temperatures existing there.

Bandy (1953) studied the Foraminifera from three suites of samples from off San Francisco, off Point Arguello, and off San Diego. He recognized a north-south variation and a depth zonation in the foraminiferal faunas. Temperature was considered the most important ecological factor in north-south variation of the shallower-water faunas, but he offered no explanation for latitude variation in the deeper-water faunas where the temperature is nearly constant. Bandy suggests also that temperature is the dominant ecological factor controlling the depth zonations, but he points out that other factors may be important since depth zonations are present where no temperature gradation exists. Five depth zones were established:

Brackish (Polyhaline) zone	
Middle-neritic zone	0–150 ft.
Lower-neritic zone	150–600 ft.
Bathyal zone	600–6,000 ft.
Abyssal zone	6,000 ft.

METHOD OF STUDY

FIELD METHODS

The field work was carried out during eight cruises. On the first cruise of February 5, 1952, sediment samples were taken from the entire area of Todos Santos Bay. During cruises on March 3, April 24, June 4, July 16, August 28, October 9, and November 10, sediment samples were obtained from a long traverse extending from shallow water in Todos Santos Bay to a water depth of 600 fathoms in the open ocean. On the last seven cruises samples were also obtained from the south side of Punta Banda.

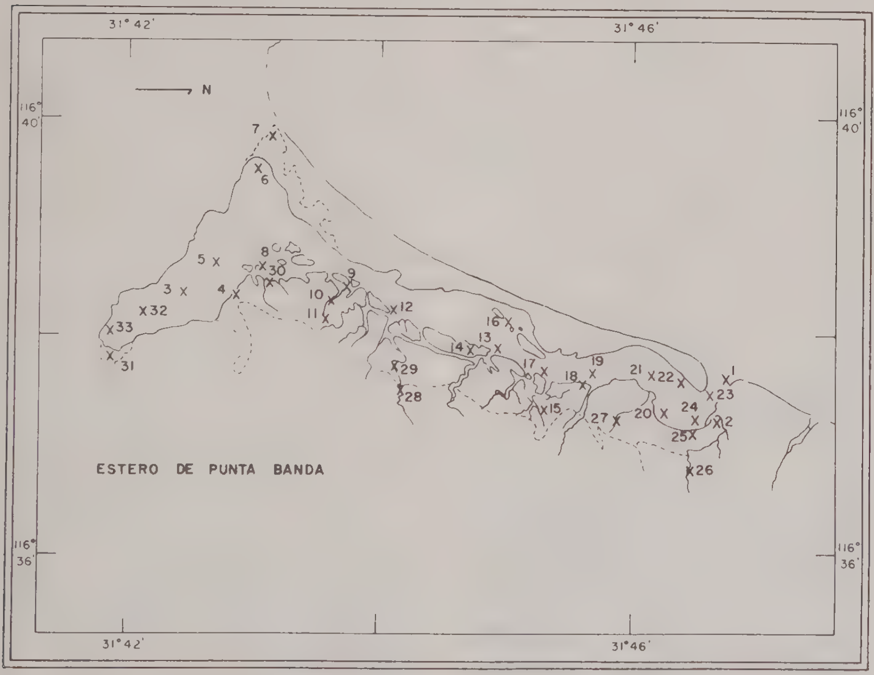
The first series of samples (February 5, 1952) were spaced at approximately 1-mile intervals on 8 traverses trending along the northeast-southwest axis of the bay (Text-fig. 2). The traverses were spaced about a mile apart, establishing a 1-square-mile grid pattern.

The stations on the seasonal traverses were spaced at 1-mile intervals to a depth of approximately 200 fathoms and at 2-mile intervals between 200 and 600 fathoms. The generalized locations of these stations are given in Text-figure 1. Actual locations of all stations are on record in the Library of the University of California at Los Angeles.

The samples taken from Estero de Punta Banda were spaced to obtain representative samples of all the environments in the tidal channels and marshes (Text-fig. 4). They were collected by hand in the marshes and by diving in the shallow channel.

A small coring tube similar to the one described by Phleger (1951b, pp. 3–5) was used where possible. It obtains a short, relatively undisturbed core $1\frac{3}{8}$ inches in diameter. In the areas of coarser sediments that could not be retained in the small coring tube, a sample was collected with a small orange-peel dredge, especially modified to prevent washing of the sediment en route to the surface (Phleger, 1952b, p. 320). This dredge has a capacity of approximately 100 cubic inches and samples a surface area approximately 10 inches in diameter.

The methods used to obtain a constant volume and area of surface sediment are extremely critical in studying either living or dead populations. A simple instrument was designed to assure constant volume sampling of all the cores and orange-peel samples. It consists of a 1 cm. length of brass tubing with the same inside diameter as the plastic core liners, and a knife edge of the same diameter pivoted on one side. As the cores were taken from the coring tube, the water in the top of the plastic liner was carefully siphoned off to within approximately one inch of the sediment-



TEXT-FIG. 4—Locations of stations in the Estero de Punta Banda.

water interface. The remaining water was then poured into a sample jar, and the core material was extruded into the constant volume sampler just described. The top one centimeter was cut off with the knife edge and was placed in the sample jar with the water.

The orange-peel surface samples were collected in a similar manner. As the orange-peel samples were brought on deck, the canvas cover was opened at the top and a short piece of plastic core liner was inserted into the sediment. This was extruded, and the top 1 cm. was cut off using the constant-volume sampler. The major difference between this type of sample and the small core sample is that the water immediately above the bottom is lost in the orange-peel sample. This water, which may contain living specimens, drains through the sample as it is brought on deck, and any specimens which may have been suspended in the bottom water tend to be trapped at the surface of the sediment.

The use of two different methods of obtaining bottom samples introduces a possible source of error in counting or estimating populations of Foraminifera. Inspection of the total populations and percentage populations of individual species in adjacent stations from which the two types of samples were obtained shows no appreciable variation that would not be expected within normal faunal variations. Distributions of sediments over the area of Todos Santos Bay (see following discussion) show normal variations and support the reliability of the samples.

All of the samples were preserved in a 10% solution of neutralized formalin. A small amount of sodium carbonate was placed in the samples to maintain an alkaline solution as the neutralized formalin will become acidic with time (see following discussion).

The stations in Todos Santos Bay were located by two-angle sextant fixes and bottom topography. Station positions outside the bay were located by dead reckoning and peloris fixes when the visibility permitted.

In addition to sediment samples, bathythermograph observations, measurements of surface water and sediment temperature, and depth soundings were taken at each station. Three times during the period of sampling, February 4, June 4, and October 9, a bathythermograph survey was made of the entire bay. Detailed temperature data also were obtained along two short traverses normal to Punta Banda on both the north and south sides at each season of sampling.

Water samples for salinity were taken at most stations in the Estero de Punta Banda and at selected stations in Todos Santos Bay.

LABORATORY WORK

Living populations were counted in 215 sediment samples. Dead populations were counted in 110 samples and sediment size analyses were run on 70 samples.

Living populations.—The living populations were determined by the rose bengal staining method (Walton, 1952). "Living" is used throughout this paper to indicate those specimens which contained protoplasm when collected. The word "dead" refers to those foraminiferal tests which did not contain protoplasm at the time of collection. The reliability of these assumptions is discussed by Walton (op. cit., p. 59). Each sample was washed through a bank of five sieves, 1 mm., 0.177 mm., 0.125 mm., 0.088 mm., and 0.062 mm. The fractions of the sediment finer than 0.062 mm. were caught in a basin below the sieves. This wet sieving procedure served three purposes: (1) it removed the fine sediment from the fractions to be examined for Foraminifera, (2) split the samples into manageable fractions for population counts, and (3) divided the sediment into size classes from which sediment analyses could be made.

It had been determined previously by experimentation that most of the Foraminifera were concentrated in the 1–0.177 mm., 0.177–0.125 mm., and 0.125–0.088 mm. size fractions. The size fractions above 1 mm. and those below 0.088 mm. contained Foraminifera attached to larger sediment particles and juvenile forms respectively. All coarser fractions were examined, but it seemed impractical to attempt to identify the juvenile forms in the finer fractions. Thus, the living populations from the three intermediate size fractions, 1–0.177 mm., 0.177–0.125 mm., and 0.125–0.088 mm., were counted separately and combined to obtain the total living populations. The total living populations from each of the samples examined are presented in Tables 1–3. The living populations of the size fractions are not presented for the sake of brevity but are on record in the Library of the University of California, Los Angeles, and the Scripps Institution of Oceanography, La Jolla, California.

As each of the samples was washed, the size fractions to be examined were placed separately in a specially-designed cylindrical sieve (average opening 0.074 mm.) and immersed in the rose bengal stain solution. The staining time is not critical. The protoplasm stains almost immediately, and only the intensity of the coloration varies with the length of time the sample is left in the solution. Approximately 20–30 minutes has been found to be sufficient staining time to obtain good coloration of the protoplasm.

The sample was then transferred to a gridded, plastic counting tray. This tray has an opaque background, and the red-colored living specimens are easily distinguished from empty foraminiferal tests and inorganic sediment particles.

The dead populations were counted along with the living populations from the wet samples except where the dead populations were very large. In the latter case it was necessary to dry the fractions of the samples and split them mechanically in order to obtain workable populations. The Otto Microsplit was used for this purpose. This small mechanical splitter has been tested statistically and shown to produce aliquots which for all practical purposes can be considered equal (Otto, 1933). The total populations of the samples from which dead counts were made are presented in Tables 4 and 6. The dead populations of the three size fractions are not presented for the sake of brevity but are on record in the Library of the University of California, Los Angeles.

SIZE ANALYSES OF SEDIMENTS

Size analyses of the sediments were obtained from the initial wet sieving. The size fractions from which the population counts were made were dried and the sediment parameters were calculated according to the procedure described by Inman (1952). The analyses obtained by wet sieving were compared with both settling tube and dry sieve analyses of the same samples and were found to be approximately comparable.

The coarser fraction of the sediments (greater than 0.177 mm.) were dry-sieved through a coarser bank of sieves of $\frac{1}{2}\ \phi$ intervals in the samples where they constituted more than 15% of the total sample. The samples in which the fine fractions (smaller than 4 ϕ [0.062 mm.]) constituted more than 15% of the sample (by weight) were analyzed by the pipette method (Krumbein and Pettijohn, 1938, pp. 162–167).

Phi notations of Krumbein (1936) have been used in the sediment size distributions considered in this study where $\phi = -\log_2$ of the diameter in millimeters. The three primary descriptive parameters suggested by Inman (1952) have been used. These three measures are the phi median diameter (Mϕ), phi deviation measure ($\sigma\phi$), and phi skewness measure ($\alpha\phi$), and are defined as:

$$\mathrm{Md}\phi = \phi 50$$
$$\sigma\phi = \tfrac{1}{2}(\phi 84 - \phi 18)$$
$$\alpha\phi = \frac{\mathrm{M}\phi - \mathrm{Md}\phi}{\sigma\phi}$$

where $\phi 18$, $\phi 50$ and $\phi 84$ represent the 18, 50 and 84 percentiles and Mϕ the phi mean.

TEMPERATURE AND SALINITY DISTRIBUTION

The annual variation in the average surface temperatures existing at the seasons of collection in Todos Santos Bay is approximately 10.0°F. There is a recorded minimum during March of 57.0°F. and a maximum of 67.8°F. during August. These temperatures correspond generally with the average maximum and minimum temperature observations made at La Jolla, California, over a period of 25 years.

During February, March, and April, the surface temperatures are strikingly uniform over the bay. The highest temperatures during these months occur around the inner part of the bay and along the mainland. During June and July, the surface temperatures inside Todos Santos Bay are considerably warmer than during the previous

TABLE *1*—OCCURRENCES OF LIVING BENTHONIC FORAMINIFERA IN ACTUAL NUMBER OF SPECIMENS. ALL FRACTIONS. (PER UNIFORM SIZE SAMPLE) (PT.)

STATION	B-34	B-72	B-73	B-127	B-150	B-240	B-277	B-357	B-467	B-52	B-92	B-93	B-111	B-53	B-35	B-110	B-348	B-94	B-109	B-151	B-241	B-278	B-358	B-468	B-469	B-54	B-91	B-108	B-128	B-347
DEPTH IN FATHOMS	3	5	5	5	5	5	5	5	5	6	6	6	6	7	8	8	8	10	10	10	10	10	10	10	10	11	11	11	11	11
TOTAL LIVING POPULATION ALL FRACTIONS	64	0	24	3	13	17	24	18	28	0	3	60	75	0	38	44	222	13	129	2	13	4	6	13	177	5	24	137	47	447
Ammodiscus pacificus																														
Ammotium planissimum															2						2				3					
Angulogerina angulosa	2																											2		
Bifarina hancocki													1																	
Bolivina argentea																														
B minuta																														
B. pacifica																														
B acuminata	1																													
B. spissa																														
B striatella															1													1		
B vaughani												1					8		2											
Buccella frigida													2																1	
Bulimina denudata																														
B exilis tenuata																														
Buliminella elegantissima					1	5	2		5			1	6			1	46					1	1	1	20					151
Cancris auricula																														
Cassidulina sp.																														
C delicata																														
C laevigata																														
C limbata																														
C subglobosa				2									2															2		
C. tortuosa																														
Cassidulinoides sp.																														
Chilostomella ovoidea																														
Cibicides fletcheri	19		16	1		6		3	13		1	19	14			4			42									54	12	
C. gallowayi	1																												1	
C mckannai																														
C spiralis																														
Cibicidina nitidula																														
Cornuspira sp.															1															
Discorbis spp.	9		1									3	3		1				6									18	2	
Dyocibicides biserialis	2											1							1									9		
Eggerella advena	1								1		1	1	2				46	2	2			1	2		7	1	3	1	2	20
Elphidium spinatum					1			2									5		1										2	3
E. translucens	1		1		1	6	15	5	4			24	26		1	27	7		5		1		1		1			1	4	9
E tumidum					7		3		2								1		40									6	1	13
Epistominella smithi																														
Eponides cf. repandus																														
Gaudryina arenaria																														
G. cf. subglabrata																														
Globobulimina spp.																														
Goesella flintii																														
Höglundina elegans																														
Labrospira cf. advena																														
L. cf. columbiensis	1												2		7		2	5	2		1				1		1			
La[illegible]nidae												1									1				2			2	3	
Loxostomum pseudobeyrichi																														
Miliammina fusca																														
Miliolidae									1			2	5		5	5			10						19			6	1	
Nonionella basispinata					2							1			7	2	4				4			8	11			2	2	16
N miocenica stella															3		24				1	2	1	1	[illegible]		1	2		228
N. sp.																														
Planorbulina mediterranensis												1																		
Planulina exorna			3																											
Polymorphinidae															1															
Proteonina atlantica					1										3		8	4	1	1	3			3	5		10	4	1	
P sp															1															
Pullenia salisburyi																														
Quinqueloculina sp	9							8									63						1							5
Recurvoides spp																														
Reophax agglutinatus																														
R curtus															1															
R gracilis																														
R horrida																														
R scorpiurus															1															
[illegible] sp. 1																														
Rhabdammina cf. abyssorum																														
Robertina charlottensis																														
Rotalia spp	9		3						2			5	12		1	4			10									19	15	
Textularia cf. schencki																														
T cf earlandi																														
Triloculina sp. 1	9															1												3		
Trochammina kelletae							4				1								2								2			
T pacifica															2		8	2	5	1					2	4	7	4		2
Uvigerina peregrina vars																														
Valvulineria araucana																														
V inaequalis																														
Virgulina bramletti																														
V seminuda																														
Unidentified forms																												1		
Planktonic forms																														

STATION	B-51	B-71	B-74	B-87	B-105	B-152	B-242	B-359	B-470	B-90	B-95	B-104	B-279	B-280	B-345	B-346	B-129	B-153	B-243	B-360	B-75	B-89	B-96	B-97	B-130	B-154	B-281	B-361	B-76	B-77	B-88
DEPTH IN FATHOMS	12	12	12	12	12	12	12	12	12	13	13	13	13	13	13	13	14	14	14	14	15	15	15	15	15	15	15	15	16	16	16
TOTAL LIVING POPULATION ALL FRACTIONS	1	19	18	63	64	10	152	85	32	37	39	35	53	20	86	152	9	4	107	47	17	32	44	23	24	21	29	61	21	8	57
Ammodiscus pacificus																			1												
Ammotium planissimum				11			2				2											2	8	4	1						16
Angulogerina angulosa					3							4																			
Bifarina hancocki												1																			
Bolivina argentea																															
B minuta																															
B. pacifica																															
B acuminata																															
B. spissa																															
B striatella				1																			2								
B vaughani																															
Buccella frigida								3											1												
Bulimina denudata																															
B exilis tenuata																															
Buliminella elegantissima							1	6	1		3				5	22	1														
Cancris auricula																															
Cassidulina sp.					1																										
C delicata																															
C laevigata																															
C limbata												1						1													
C subglobosa					1																										
C. tortuosa					1							1																			
Cassidulinoides sp.																															
Chilostomella ovoidea																															
Cibicides fletcheri					11							7																			
C. gallowayi					1																										
C mckannai																															
C spiralis																															
Cibicidina nitidula												1																			
Cornuspira sp.																										4					
Discorbis spp.																															
Dyocibicides biserialis					3																										
Eggerella advena		2	2				28	11	2	1	6	2	2	4	4	18	2		7	7	1		6	2		5	5	4	1		
Elphidium spinatum																			1												
E. translucens							1		1					1			1		6												
E tumidum												3							3				1								
Epistominella smithi																															
Eponides cf. repandus																															
Gaudryina arenaria																															
G. cf. subglabrata					5							1																			
Globobulimina spp.																															
Goesella flintii																															
Höglundina elegans																															
Labrospira cf. advena			1																												
L. cf. columbiensis		2		25	6	2	27	4	6	11	12		27	5	7	7			26	12	3	10	7	4	1	1	6	20	8	1	11
La[illegible]nidae							2																								
Loxostomum pseudobeyrichi																															
Miliammina fusca																															
Miliolidae							2												1												
Nonionella basispinata					2	4	28				3	1	13	4	9	13			26	14			5	5			11	15		2	
N miocenica stella							39	58	13	4			4	3	61	89			7	10				4			7	9			
N. sp.																															
Planorbulina mediterranensis																															
Planulina exorna					4																										
Polymorphinidae										1																					
Proteonina atlantica		6	2	20	1	4	16	1	7	12	9	2		2		2	2	2	15	4	8	17	3	2	18	5		12	11	2	18
P sp																							1	2							
Pullenia salisburyi																															
Quinqueloculina sp																															
Recurvoides spp				1																											
Reophax agglutinatus																															
R curtus																															
R gracilis																															
R horrida																															
R scorpiurus												1											2								
[illegible] sp. 1																															
Rhabdammina cf. abyssorum																															
Robertina charlottensis																															
Rotalia spp				2	6							2																			
Textularia cf. schencki					4																										
T cf earlandi																															
Triloculina sp. 1																															
Trochammina kelletae					2						2																				
T pacifica	1	9	13	3	7		6	2	2	8	2	8	7	1		1	3	1	13		5	3	9		3	6		1	1	3	12
Uvigerina peregrina vars																															
Valvulineria araucana																															
V inaequalis																															
Virgulina bramletti																															
V seminuda																															
Unidentified forms					6																				1						
Planktonic forms																															

Table 2—Occurrences of Living Benthonic Foraminifera in Actual Number of Specimens. All Fractions. (Per Uniform Size Sample) (Pt.)

STATION	B-244	B-471	B-70	B-78	B-131	B-55	B-282	B-362	B-36	B-68	B-69	B-103	B-344	B-50	B-79	B-85	B-86	B-245	B-472	B-63	B-80	B-81	B-84	B-132	B-155	B-62	B-56	B-64	B-67	B-37	B-44	B-83	B-102	B-66	B-49	B-65	B-149	B-48	B-57	B-363	B-38	B-338	B-291	B-42	B-482	B-43	B-156	B-252	B-267	B-306	B-498	B-381	B-330	B-133	B-39	B-61	B-58	B-47	B-59	B-60	B-483
DEPTH IN FATHOMS	16	16	17	17	17	18	18	18	19	19	19	19	19	20	20	20	20	20	20	22	22	22	22	22	22	23	24	24	24	25	25	26	26	27	28	28	28	30	31	31	35	35	38	39	39	40	43	45	47	47	54	55	62	64	68	92	96	108	110	110	118
TOTAL LIVING POPULATION ALL FRACTIONS	102	55	21	22	26	63	32	443	63	42	33	136	381	65	103	71	115	347	61	59	39	40	67	117	105	55	13	154	67	93	14	124	60	105	44	230	29	91	117	164	155	923	101	22	147	46	169	255	47	43	60	187	279	183	103	40	144	80	88	43	67
Ammodiscus pacificus																																																			10	5									
Ammotium planissimum	2						1	6	1		1		1		1			5	3					16	2		2		2	1				4	1	2		14	11	8		3	1		13		7	5	4	1		3		36	1						
Angulogerina angulosa									1			3				6	3			3	3	2						3		5	3	5	2		1	4					2			1		2	1						3					1			
Bifarina hancocki																	2													1				4																											
Bolivina argentea																																																													
B. minuta																																																													
B. pacifica								2					4					8				1												2			1		4	1	4	6	3		4			1		4	5	50	114		1	4	5	9	3	8	7
B. acuminata																1		6																				1		3	5	8	2		2	2	20	9	8	3	12	26	2	3	3	15	16	9	11	4	2
B. spissa																																																													
B. striatella										1					1		2	4				1		1	4					11				7		7	16		2	1	10			1	1		1	1		2	2	8			6		1				
B. vaughani																	1																				2		2		1												2								
Buccella frigida						2			3				1		1			4	3	1				3						5				1					2	1	2	2					1							3	4		1	1			
Bulimina denudata																		2												1				1					2		1	1			3		1	2	1					9			20	15	27	10	4
B. exilis tenuata																																																													
Buliminella elegantissima					4																			3																																					
Cancris auricula																						1								1						1	5				1					2	1			1	1	4	15		1			1			
Cassidulina sp.																1																				5											5	3						2		1	1				
C. delicata																																																													
C. laevigata																																																													
C. limbata																6	1				3		7			3						25	5													11				2						1					
C. subglobosa												16				16	5			4	6	1	6			3		12		6		34	13	1		17			2		4			4		2			1				3	1	4		6	4	2	1	
C. tortuosa												16			2	2				6	5	6	11			31		21		1		5					1									14															
Cassidulinoides sp.																																																													
Chilostomella ovoidea																																																				1	6		6					2	
Cibicides fletcheri									7			47				17	4			28	14	10	13			6		81				26	21			8					3			6		6	3										4		11	2	
C. gallowayi												1				1					1		2					2													1																				
C. mckannai																							2							1		3										4						6	2	4				2							
C. spiralis																																																													
Cibicidina nitidula												2				2	1					1	1					2		1		3	1				2													1											
Cornuspira sp									1																			1		8											2																2		1		
Discorbis spp.			1						4	5		2		4			1				1															15						1																	1		
Dyocibicides biserialis																					1							3			2																														
Eggerella advena	9	5	1		4		1		1	1	3		1				3	4				1	1						1												2							1						1							
Elphidium spinatum																																																													
E. translucens	26								1						1		1	1																																											
E. tumidum	2				3				3	1					4		6															2	1	1		1																									
Epistominella smithi																																																													
Eponides cf. repandus																										1																																			
Gaudryina arenaria														2																											1	1			2							3		2							
G. cf. subglabrata												5				1							2					1					1			1								1																	
Globobulimina spp																																							1	2	7	4					4	5	5	4	9	14	52	5	33	8	25	26	8	10	16
Goesella flintii								2					6					8	2					21	2		2		6	2				6	1	5		6	3	23	1	14	1		46		6	32			1	4		4			1				5
Höglundina elegans																																																													
Labrospira cf. advena			1			1			1		1			13	2									2					4	6								1	1		3	7						7													
L. cf. columbiensis	19	2	3	9	2	5		1	1		1	1	1		3		25	1	1			2	1	2	2		2	1	2	1				1		5	1		6	9	6	9	5		5		3	6	8	6	12	6	2		1	5	3			2	4
Lagenidae															2										1					1				1		2											3										2	1			
Loxostomum pseudobeyrichi																																																													
Miliammina fusca												1			1		3													2																															
Miliolidae							1					15			2	1				2			3					3								4																									
Nonionella basispinata	21	8		1	2		2	48	9			3	39		25		19	90	12	2	2	2		11	50			2		1	1		3	10	1				8	14	4	39	8		1		28	31	4					1				1			4
N. miocenica stella	8	26	2				16	374	9	1			304		5		6	177	11			1		8	33				3	13	2			33	4	36		4	24	62	77	[illegible]	71		36		58	120	14	6	2	99	45	76	34	5	26	8	6		14
N. sp																																								1		7			2						4		15								5
Planorbulina mediterranensis																												1			1																														
Planulina exorna							1					4				3				2	1	4	3			1		1				8	4			2				2				3		4	3								1			1			
Polymorphinidae															1	1	2						1					1		3		1	2														1														
Proteonina atlantica	2	12	5	9	7	14	4	2	3	2	12	1	9	4	24	1	3	13	4			1	3	12	6				4			2	2	3	1			2		5			3	3			3	5		3				1			2	1	5	2	
P. sp	1																		7					2					2	1					1			2	6		1		2	1	6		3			1	3	2		26	1		1				
Pullenia salisburyi																																				1																							1		
Quinqueloculina sp																																																													
Recurvoides spp											2													3			1		3					1	2	4		8	13	1	3	6			15					2				9			2	1			1
Reophax agglutinatus															2														1																												3				
R. curtus			2			15	1				1			6				6						5	2				6	4				6	5	14		17	12	2	5						3														
R. gracilis							2	3										9				1					1							1				1	4	5	2	1	2					1		3	4	6	19	2	3	1		4		1	
R. horrida																																																				2									1
R. scorpiurus			1	2		1		4			4		2	6	8		2	5	8					25	2		3		14	4					5	8		33	10	3	1	2	1		8		6	4				2									
R. sp. 1																																																													
Rhabdammina cf. abyssorum													X					X							X															X		X	X																		
Robertina charlottensis																			2																							6					2				1										
Rotalia spp.								1	8	1		17			7	6	12			7	1	1	8					14		1	4	3	2	2		20				3						1	2														
Textularia cf. schencki												1			1	1	1			1			2			2						3								4		5		1	3			2							1			1	1		
T. cf. earlandi																								1																		2																			
Triloculina sp. 1	6												10				2			1	1	1									1	1		2								4						14													
Trochammina kelletae	1				4				2													2	1					3				3	3																												
T. pacifica	5	2	11	1		25	3		8	23	8	1	3	20	10		10	4	2	2				2	1	8	2		8	8				7	9	8	1	2	4	3		1		1		2	2					2									
Uvigerina peregrina vars																						1																															1		2		23	2	11	1	4
Valvulineria araucana																																																													
V. inaequalis																																																													
Virgulina bramletti																																																													
V. seminuda																																																													
Unidentified forms										7				10		5												2	11	4				11	13					11	7	13	2				2								1						
Planktonic forms									4																					6								1																							

Table 3—Occurrences of Living Benthonic Foraminifera in Actual Number of Specimens. All Fractions. (Per Uniform Size Sample) (Pt.)

STATION	B-253	B-292	B-337	B-293	B-364	B-157	B-45	B-134	B-365	B-254	B-46	B-116	B-135	B-317	B-271	B-336	B-484	B-377	B-310	B-158	B-502	B-326	B-366	B-294	B-485	B-136	B-255	B-486	B-137	B-256	B-318	B-257	B-296	B-367	B-368	B-487	B-161	B-295	B-160	B-138	B-118	B-297	B-319	B-258	B-488	B-369	B-298	B-489	B-320	B-140	B-139	B-259	B-490	B-321	B-141	B-260	B-491	B-371	B-300	B-261
DEPTH IN FATHOMS	120	120	122	125	127	130	141	145	147	148	150	153	154	155	165	165	167	169	175	177	187	189	195	203	205	215	215	217	230	235	238	240	245	245	248	248	250	250	265	266	275	320	320	325	325	340	350	360	365	375	380	400	450	480	490	550	590	595	600	620
TOTAL LIVING POPULATION ALL FRACTIONS	170	40	167	88	39	25	102	44	72	77	17	16	8	32	37	42	42	11	13	2	23	45	31	63	13	8	35	33	7	18	2	11	14	17	13	11	7	28	39	14	137	32	18	53	48	31	127	19	40	108	108	30	24	23	20	4	15	5	11	46
Ammodiscus pacificus																																																												
Ammotium planissimum				2		3		1									1	5	1		1	2	1				2				1	3			1		1					2		6	8		2				1									
Angulogerina angulosa																							1		1																							1												
Bifarina hancocki																																																												
Bolivina argentea																		1	1		1	2	2	3	2					2			1					1			66			18																
B minuta																																	1			3		1	2					1						1	1		1		2					1
B. pacifica	35	13	28	21	13	1	32	9	22	10			1	2	1	7			3			4	1	11		1	1												2			1					1							1	1					
B. acuminata	2		2	3			1			1					1				1					1	1			1								1	1																							
B spissa																						1							1					1	1				10		8	8	4		13	9	31	2	13	18	31	11	10	11	4	1		2	2	11
B. striatella																																																												
B vaughani								1																		1																																		
Buccella frigida			7																																																									
Bulimina denudata	22	1	9	7	7	3	13	6	1	3	5	5	2			1						1					1																																	
B. exilis tenuata																																															6													
Buliminella elegantissima								1								1																							1																					
Cancris auricula				1				1						4									8	2															2																					
Cassidulina sp.	1					1																				1															1																			
C. delicata																																						1			7	3		2		1	7	6	6	2	4	3	2	5	3			1		9
C laevigata																																						1			6			3				7		1	19		1		3		4			
C limbata																																																												
C subglobosa	1			5			5			1																																																		
C. tortuosa																																																												
Cassidulinoides sp.														2										2																																				
Chilostomella ovoidea	1	1						3		1				1										8			1			1					1		2					9	3	4	4	7	17		4	46	12				1					14
Cibicides fletcheri																											1																																	
C gallowayi																																																												
C mckannai																																																												
C. spiralis																																																												1
Cibicidina nitidula																																																												
Cornuspira sp.																																																												
Discorbis spp.																																																												
Dyocibicides biserialis																																																												
Eggerella advena																																																												
Elphidium spinatum																																																												
E translucens																																																												
E. tumidum																																																												
Epistominella smithi																											1														1			2			1			2		1			1					
Eponides cf. repandus																																																												
Gaudryina arenaria	2																																																											
G. cf. subglabrata																																																												
Globobulimina spp	79	16	59	23	4	9	38	17	6	42	5	3	3	12	17	16	4	2	2		4	19	2	4		2	18	28	6	12	1	1		9				14		6	3	3	1		1	1	2	1	1	21	2		1		2	1				1
Goesella flintii				3	3	1			1	1			1	4		3							6	8	5	1	3					1	3	5	2	1	3	3	3		23			1						2	1									
Höglundina elegans																																																				3	5	2			1	1	1	1
Labrospira cf. advena																																																												
L. cf. columbiensis	3		3	1	1						2	1												2			1												1																					
Lagenidae												1																																							1									
Loxostomum pseudobeyrichi																																															4		1	2	3	2					1			
Miliammina fusca																																																												
Miliolidae																					2	2																																						
Nonionella basispinata			2																																																									
N. miocenica stella	3	4	17	2	7	5	7	3			1						1									1																																		
N sp	14	3	27	7	1				36	18				3	14	13	32	2	2		11	7	1	1	3		2							2	2	1		1				1	8	1			9													
Planorbulina mediterranensis																																																												
Planulina exorna																																																												
Polymorphinidae																																																												
Proteonina atlantica				1		1							1											1																																				
P sp		1										3							1	1													3			2		1	3						11	2	30	1	6	3				1						
Pullenia salisburyi																								3																												1								
Quinqueloculina sp																																																												
Recurvoides spp							1	1								1																			1				5										2		2								2	
Reophax agglutinatus				3																																																								
R curtus																																																												
R gracilis	2	1	2	1		1	1	1	1			2		2			2		1	1	2	3		1		1	2			2										2							1			1										
R horrida																	1				1	1						1										1			10				5	9	1		1											
R scorprurus																																																												
R sp. 1																																										1	1	1	2		3	1			10	1					6	1	4	5
Rhabdammina cf abyssorum																																																												
Robertina charlottensis			1																																																									
Rotalia spp.																																																												
Textularia cf. schencki																																																												
T. cf earlandi																																																												
Triloculina sp. 1																																																												
Trochammina kelletae																																																												
T pacifica	1										3																																																	
Uvigerina peregrina vars	4		9	8	2		3				1			2	1							1	3							1		6	6		5	3		4			10			3	1	1	2		3	3	2	1	1	3	2				1	2
Valvulineria araucana																							4	8															2				1	4	3		5		1	1	4	2	1				3			1
V inaequalis																								1			1												2					1			1		2			1				2				
Virgulina bramletti					1										3				1			1																				3		6			4					1							1	
V seminuda									5								1	1			1	1	2		1		1	3											4			1				1				1										
Unidentified forms			1				1					1												7															2	6	2									4	15	3	2		1					
Planktonic forms							8						1																																															

Table 4—Occurrences of Dead Benthonic Foraminifera in Percent of Total Population. All Fractions. X Less than 1%.

STATION	B-34	B-35	B-36	B-37	B-38	B-39	B-42	B-43	B-44	B-45	B-46	B-47	B-48	B-49	B-50	B-51	B-54	B-55	B-56	B-57	B-58	B-59	B-60	B-61	B-62	B-63	B-64	B-65	B-66	B-67	B-68	B-69	B-70	B-71	B-72	B-73	B-74	B-75	B-76	B-77	B-78	B-79	B-80	B-81	B-83	B-84	B-85	B-86	B-87	B-88	B-89	B-90	B-91	B-92	B-93	B-94	B-95	B-96	B-97	B-102	B-103	B-104	B-105	B-108	B-109	B-110	B-111	B-116	B-118	B-135	B-136	B-137	B-138	B-139	B-140	B-141	B-141-1490
DEPTH IN FATHOMS	3	8	19	25	36	68	39	40	25	141	150	108	30	28	20	12	11	18	24	31	96	110	110	92	23	22	24	28	27	24	19	19	17	12	5	5	12	15	16	16	17	20	22	22	26	22	20	20	12	16	15	13	11	6	6	10	13	15	15	26	19	13	12	11	10	8	6	153	275	154	215	230	266	380	375	490	490
TOTAL DEAD POPULATION ALL FRACTIONS	1 154	673	648	1 610	579	973	13 218	12 520	7 264	506	257	216	92	79	162	4	19	121	56	269	373	413	952	1 087	771	11 652	13 296	12 960	1 370	199	153	111	190	141	4	38	125	59	22	85	311	903	3 501	10 088	12 936	18 592	6 624	8 702	199	94	86	44	20	2	173	24	155	391	1 621	202	659	169	2 304	12 104	6 632	569	698	376	638	421	5 704	302	862	567	3 411	1 928	1 056
Ammotium planissimum			X	X	X	2				1	1	X	8	10	2				11	9	1	3	X					X	X	2	X	6										X						X	5	18	4						2	11	1										X					X	X		
Angulogerina angulosa	2	2	1	10	4	5	4	12	2	X	X	X											X	5	X	1	2	4	2	X													5	6	8	9	6	6							2			1	5	7	3	1	2	1	X	1	X	2		2	5	5		2	1	4	
A. carinata																																																																						X	X		X			2	X
Astrononion stellatum																																																																								X	X	X	X		
Biforina hancocki	3	9	X	2				X	2		1			1						X								X	X		X													X	X			X											X					X		X	1										
Bolivina acuminata	X			X	3	10		X		X	2	11		1							12	5	5	15																																								X				2		1		1					
B argentea										4	2	X																																																									8	45	3	11	7	2	X	X	5	25
B. minuta																																																																						X	X	4	5	3	5	4	
B pacifica				X	4					28	46	11									9	1	6	3					X																																							22		20	X	4		X			
B. pseudoplicata							X																																																																1	1					
B. seminuda								X															X																																																					3
B. spissa										X																																																												3			X	8	5	7	7	7
B striatella	X		X	2	9	1	X	X	X		X			3						3	X	X	X	X	X			X	2													X	X	X			X	X									X	X							X					X						
B. vaughani		2	X	1	X	2	X	X	2	2	7	X									2	1	2	X			X	X	X					X								X		X	X										X				X		X	X			X	X		3		5	X	2	X	1	X	X	
Buccella frigida			3	15	5	3	X	X				3		4						2	3			11				X	10		6											9	X	X				2	1						1			2	16					2	X	4	2	3	X	5	2	4		X			
Bulimina denudata			X	2	2	2			X	9	7	6								X	11	19	17	5				X	1		1											X													X				X						X			10		9	X	1					
B exilis tenuata																																																																									X		X	2	10
B. pagoda																																																																												X	5
B subacuminata																																																																										X	X	3	1
Buliminella elegantissima	X	X		X	X																		1						12													5						X	2						4	8	3	3	2							X	4				1	X		X			
Cancris auricula			X	X	X	X		X	X	X																		1	X															X																											X						
Cassidulina californica																																																																								X						
C. delicata																																																																					1				28	40	29	15	2
C. laevigata																																																																					3				23	11	27	13	
C. limbata					X	2	4	5	X												X		X	X	5	1	2	X														X	3	1	3	3	3	X								4				4	X			X	X		X	X			3	X				2	
C subglobosa	X	5	6	22	24	12	25	29	1	5	1	31	1	1				X		2	15	18	3	8	16	8	7	21	12													12	12	11	14	13	16	17	1						X		X	X	8	19	37	5	X	3	4	2	1	1	X	4	6	3	3	2	X	8	
C tortuosa				X		X	X	6	X	X															47	6	8	3															22	21	39	18	20	5	X											2	6	6	38	1	1						X						
C sp.				X			X	4	X									X			X	X	22	20	X	X	X	4	X													X	X	1	X	X	X	1											X		1		X					2	1	4	2	7	3	14	7		2
Cassidulinoides sp.																																																																				2									1
Chilostomella ovoidea						X				X	X										X			X																																																X	1	X	4	1	X
Cibicides fletcheri	19	2	6	4	6	22	39	19	21	1		X									2	15	6	7	21	49	49	27	4	2			X		25	90						3	35	34	20	31	40	33	5	2				100	31			4	25	37	21	53	41	27	38	34	26	12	3	10	6	15	X	1			
C gallowayi	1		X				X		X														X				2		X														1	1		X	1	1													X	1	3	X							X						
C mckannai					X	7															X	X							X																3	X																											X		X		2
C spiralis																																																																											1	X		
Cibicidina nitidula		X	X	X	X	X	X	1	X														X	X			X	X							25							X	2	X	X	X	X	1												3	X			X	X						X						
Cornuspira sp.	X	X		X			X	X	1		X	X						X				X	X		X																					X		X																													
Discorbis spp.	9	25	4	X	X	1	5	2	24	3		X			1			X		X	X	X	1	1		2	2	18					X	3								X	5	4		X		5	1						9	4		2	X	8	4		X	29	22	20	17			1	11	1					
Dyocibicides biserialis	X						X	6	X																X	X		X															X	X											2										X						X						
Eggerella advena		4	7														21		2	2			X			X			2	31	X	14	4	11			38	7		5	15	6		X					8	18	14	9	5			25	38	13	4		X			X	X			X		X							
Ehrenbergina compressa																																																																										X		X	1	
Elphidium crispum																											X																			X	X																														
E spinatum			X																																							X													1				X						X		1				X						
E translucens		3	X																							X	X	X	X							3						1						3	3						9			X	X							13	21				8	X					
E tumidum			4	X			X		X																		X	1	20	2	7			X								14	X	X		X	X	2	1						X			8	16		X			X	4		X										
Epistominella smithi																											X																			X																							X	1	X	2	4	3	9	5	3
Eponides cf. repandus								X	X																1	X																	X	X	X	X	X														X		X														
E. subtenera																																																																							X	X				2	3
E umbonatus																																																																											X	
Gaudryina arenaria				X	1	3							2										X	2				X	X													X		X																				X				X			X						
G cf subglabrata							2	X																		X	X	X																X		X	X	X											X	2	3		X	X						X	2	1			X		
Globobulimina spp.						4				23	15	11									12	23	8	4																																												11	2	14	2	23	5	2	1	2	1
Goesella flinti		X	X	X									1	8					21	7	X							X	X	1		2										X																											21			X		X			
Gyroidina altiformis								X																				X	X																																							X			X					X	3
Höglundina elegans																																																																											X	X
Labrospira cf advena			3	X	X		X								4			2	4	X									X	2		3	2				X		4			X							2																												
L cf columbiensis	X	3	X	X	X	X					1						5	7		X	X			X					X		2	2	5	4	25		6	5	18	11	12	X						X	15	26	7	4	15			25	22	10	3		X		X	X	X	X		2									
Lagenidae	X	1	1	4	1		X	X	X	2		X		3						X		X	1	X		X	X	X	3	X	X											4	X	X	X			X							X			1	X			X		X	X	X	1				1	2	X	X	X	X	
Loxostomum pseudobeyrichi					2																																																																				X	X	X	X	5
Miliammina fusca							X	X	X																																		X				X																	X		X												
Miliolidae	14	2	2	X				2	9										2						X	2	2	X						1								X		2	2	3	X	X							5				X		2		1	3	2	X											
Nonionella basispinata	X	13	9	8	2	X	X	X	X		1		5	1						3				1		X	X	1	8	X	3											6	X	X				2	2			2			4		2	4	4		X	X	X	X	X	X	1	X		3	3	X	X	X			
N miocenica stella			3	5	19	4	X		X	4	2	5	7	1			10			12	15	2	6	6				3	9	6	6			X								2		X				X									X	X	1				X				X	X		3	13	X				X	
N sp.																																																																									X	X	1	X		
Planorbulina mediterranensis						X			X																																														X																						
Planulina ariminensis						X																			X																																														X					2	2
P exorna			X	1	2	5	4		1	3	X	X		1							1			X	X	2	4	3	X		X					3						X	8	4	7	6	4	6							1				X	5	2		3	X	1	X	X	X	1	X	1	1	X	X	X	3	2
Polymorphinidae		X		X					X				1	1												X																X			X	X		X												X	X		X														
Proteonina atlantica		X	3	X						1	X	X	6	8	6		16	32			X	2					X		X	7	3	18	13	18			6	42	68	48	27	5							17	17	94	41	50			12	11	23	2		X			X						X							
P sp		X							X											2	X	1	1	X				X		4												X																X	X																		
Pullenia salisburyi						X																X		X	X																																											X			X	X				X	
Quinqueloculina sp.	6																																																																												
Recurvoides spp.					X					1		X	7	1					7	11	1		X						X	1																																												1			
Reophax agglutinatus				X	X					X											X			X																																															X						
R curtus		X	X	X	X					X			15	25	2			4	9	23							X	X	X	4		8	3															X																													
R gracilis					X	X	X			X	2	X	5	3					4	3			X	X																																												1									
R horrida																																																																					6								
R scorpiurus		1	1	X	X								27	14	24			5	27	13								X		4	X	3	X								X						X																														
R sp 1																																																																											X			
Robertina charlottensis				X			X																																			X		X																																	
Robulus sp.			X					X																																																												X			X					X	X
Rotalia spp.	39	X	12	6	5	7	12	13	24											X	1		5	2	6	26	18	6			2			X		5	X					2	4	7	2	5	6	10	2						25			3	6	13	17	28	8	31	23	21	22	7	X	1	X	X					
Rudigaudryina inepta							X																																																																						
Rupertia cf stabilis																																																																								X						
Sigmoilina cf miocenica																																																																							X	X	1	1	X	X	2	3
Textularia cf schencki			X	2	1	3	X	X		X		1									X	X				X	X	X	X													X	X	X	X	X	X	X											X	X	X		X							X	X						
T cf earlandi										X																																																																				
Triloculina sp. 1	4		X				2	X	4																	X	X																X	X	X			X																X	X	X											
Trochammina kellettae	X		X			X	X			7	9	5	8	4	3				7		X	2	4	X					X			4									X	X		X	X				X								3	X			X			X				4		1		X		X		2	
T pacifica		21	25	8	X	X	1	2	X	X		2	5	9	55	100	47	46	7	2	X		X			X	X	5	31	65	40	72	61	25			49	46	9	34	43	22		X				2	35	19	22	43	30		1	17	19	10	2	X	X	4	X	X	X	X	1				2						
Uvigerina peregrina vars				X		X		X			2	7									10	3	3																																													4	11	1	9	9	8	2	1	8	8
U senticosa																																																																											2	
Valvulineria araucana												X										X		X																																														2	X		X	3	X	X	9
Virgulina bramletti																																																																										X	X	X		
V seminuda																																																																								X		X	2	X	X	X	
Unidentified forms		X		1					X						2							X		X			X	X	2	X											2	X																																			

months. They average about 61.0°F. but reach 65.0°F. around the inner part of the bay and along Punta Banda. The mixed layer is shallow; only 5–15 feet during these months.

The most interesting feature of the temperature distribution in June and July is the occurrence of upwelling on the south side of Punta Banda. During February, March, and April the difference in temperature between the north and south sides of Punta Banda is small, averaging only a few degrees. In June the temperature difference between the north and south sides of Punta Banda is 9–10°F. Dr. Carl Hubbs of the Scripps Institution of Oceanography (personal communication) has found temperature differences as great as 21°F. During July this cold, upwelled water extends along Punta Banda as far as the Todos Santos Islands and extends around Punta Banda a short distance into Todos Santos Bay.

The highest surface temperatures of the year occurred in August. Temperatures as high as 71°F. occurred in the inner part of the bay. The water on the south side of Punta Banda increased to 59°F., but there was approximately 10°F. differential across the point.

During October and November the water temperature in the bay gradually decreased to approximately 61°F. Upwelling on the south side of Punta Banda apparently diminished during these months and the water temperature was approximately the same as that of the bay water.

The influence of the warmer waters from the Estero de Punta Banda on the open bay waters is noticeable during the spring and summer months. The water in the Estero de Punta Banda flows in and out with the tidal cycle and the warmest water in the bay during these months generally occurs near the mouth of the estero. The tidal range in this area is approximately 3.8 feet. The water temperatures in the shallow estero are quite variable and range from approximately 60.0°F. near the mouth to more than 85.0°F. near the head. Estero temperatures were only measured during November, 1951, along with the collection of the estero samples and no seasonal data are available.

Salinity measurements from samples corresponding with the seasonal traverse in the bay show fairly uniform surface salinities of approximately 33.40°/$_{oo}$. Since these samples were collected during February they probably represent minimum salinity values, because this is the rainy season in this region. The seasonal variations of salinities in the open ocean off Punta Banda show variations from approximately 33.40°/$_{oo}$ in the winter months to approximately 33.70°/$_{oo}$ during the spring and summer months, according to Paul Horrer (personal communication). It is believed that the range of salinity given is representative of the range occurring in Todos Santos Bay.

The salinity measurements in the Estero de Punta Banda show greater variation. Near the mouth of the estero the salinities range from 33.40°/$_{oo}$ to 33.98°/$_{oo}$. The channel stations all show salinities between 33.63°/$_{oo}$ and 34.00°/$_{oo}$. The highest salinities occur near the head of the estero and from the tidal channels away from the main channel. These salinities are all greater than 34°/$_{oo}$ and range up to 37°/$_{oo}$. The salinities in the Estero de Punta Banda probably vary considerably during the various seasons. Rapid runoff must lower the salinity considerably during the winter rainy seasons. During the spring and summer months the salinity would probably increase due to high temperatures, no precipitation, and evaporation.

THE SEDIMENTS

SEDIMENT TYPES

Seventy samples were analyzed from Todos Santos Bay. Size analyses of the sediments were made from all the stations listed on Text-figure 2 with the exception of stations B-40, B-41, B-82, B-98, B-99, B-11, B-101, B-106, and B-107, from which no samples were obtained. The sediment samples were subjected to the standard methods of mechanical analysis, and from these data phi median, phi deviation, and phi skewness were calculated. These parameters are presented in Table 5. The sediments of the area fall generally into three groups based on a plot of the phi median against phi deviation and phi skewness (Text-fig. 5). The geographic distribution of

TABLE 5.—SEDIMENT SIZE DISTRIBUTIONS

Sta. no.	Depth (fms.)	Mdϕ	σϕ	αϕ
B-34	3	2.37	.87	.18
B-35	8	1.76	.50	0
B-36	19	3.20	.40	0
B-37	25	2.98	.70	−.01
B-38	35	3.68	.60	−.33
B-39	68	3.85	1.40	0
B-42	39	.97	1.43	−.05
B-43	40	.25	1.10	.26
B-44	25	−.50	3.10	−.09
B-45	141	5.95	1.80	.13
B-46	150	5.41	1.84	.40
B-47	108	5.45	1.36	.25
B-48	30	4.28	.72	.22
B-49	28	3.75	.70	−.06
B-50	20	3.27	.34	.11
B-51	12	2.92	.38	−.10
B-52	6	3.57	.25	.04
B-53	7	3.27	.24	−.05
B-54	11	3.22	.34	0
B-55	18	3.50	.29	0
B-56	24	4.27	.46	.23
B-57	31	4.65	.61	.32
B-58	96	5.06	1.26	.47
B-59	110	5.45	1.70	.34
B-60	110	5.85	1.55	−.05
B-61	92	5.23	1.11	.23
B-62	23	1.45	.50	0
B-63	22	2.16	.60	.03
B-64	24	2.10	.70	−.04
B-65	28	3.49	.72	−.48
B-66	27	4.20	.31	.26
B-67	24	3.99	.36	.11
B-68	19	3.91	.28	.08
B-69	19	4.02	.42	.28
B-70	17	3.57	.19	0
B-71	12	3.42	.61	−.05
B-72	5	3.10	.33	0
B-73	5	2.80	.28	0
B-74	12	3.70	.32	0
B-75	15	3.65	.32	.03
B-76	16	3.63	.27	.14
B-77	16	3.77	.29	0
B-78	17	3.92	.34	0
B-79	20	3.98	.37	.03
B-80	22	2.47	.50	−.14
B-83	26	1.92	.50	−.18
B-84	22	2.40	.73	−.05
B-85	20	2.40	.57	−.07
B-86	20	3.51	.76	−.06
B-87	12	3.93	.34	−.06
B-88	16	3.73	.38	0
B-89	15	3.70	.44	.12
B-90	13	3.61	.36	.33
B-91	11	3.62	.34	−.03
B-92	6	3.20	.28	−.03
B-93	6	3.48	.30	−.07
B-94	10	3.65	.41	.09
B-95	13	3.72	.50	.12
B-96	15	3.91	.48	.16
B-97	15	3.93	.39	−.01
B-102	26	2.25	.48	−.12
B-103	19	2.49	.42	−.05
B-104	13	2.55	.65	−.23
B-105	12	1.34	.93	.24
B-108	11	3.65	.38	−.10
B-109	10	3.44	.50	−.10
B-110	8	3.87	.49	.02
B-111	6	3.47	.45	−.02
B-116	153	5.80	1.50	−.03
B-118	275	5.46	.78	−.29

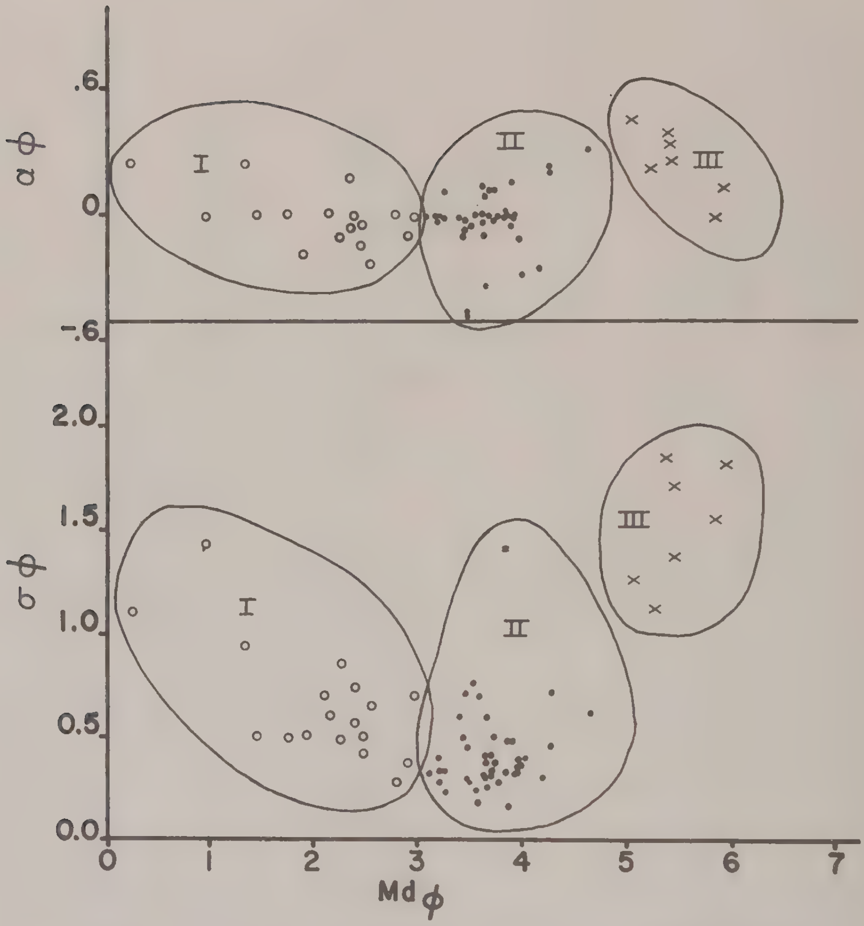
these groups is presented in Text-figure 6.

It should be pointed out that in most instances the amount of sediment available for particle-size analysis was less than 10 grams. It is believed, however, that the descriptive parameters obtained from the particle-size analysis are adequate for the purposes of this study.

The sediments of Group I occur in a strip between the Todos Santos Islands and the mainland on the north side of the bay. They also occur along Punta Banda and at one station near the mouth of the Estero de Punta Banda. This group of sediments is relatively coarse. The Mdϕ ranges from less than 1ϕ to 3ϕ, the sorting is poor, the phi standard deviation is generally greater than 0.50ϕ, and the sediments are generally skewed toward the coarser sizes. They are most generally brown in color, and many samples contain well-rounded pebbles and cobbles.

Microscopic examination of the Group I sediments shows very large populations of Foraminifera. The pebbles and cobbles are encrusted with bryozoans and attached Foraminifera suggesting little or no transportation or agitation of the bottom at the present time. Glauconite occurs in low percentages in the form of internal molds of Foraminifera and suggests extremely slow sedimentation. Fine detrital sediments occur in most of the samples along with the more predominant coarser sizes and cause slight bimodal tendencies in some samples. All of the samples contain abundant shell fragments (other than Foraminifera) and broken echinoid spines.

The Group II sediments cover most of the bay area with the phi medians ranging for the most part between 3ϕ and 4ϕ. They

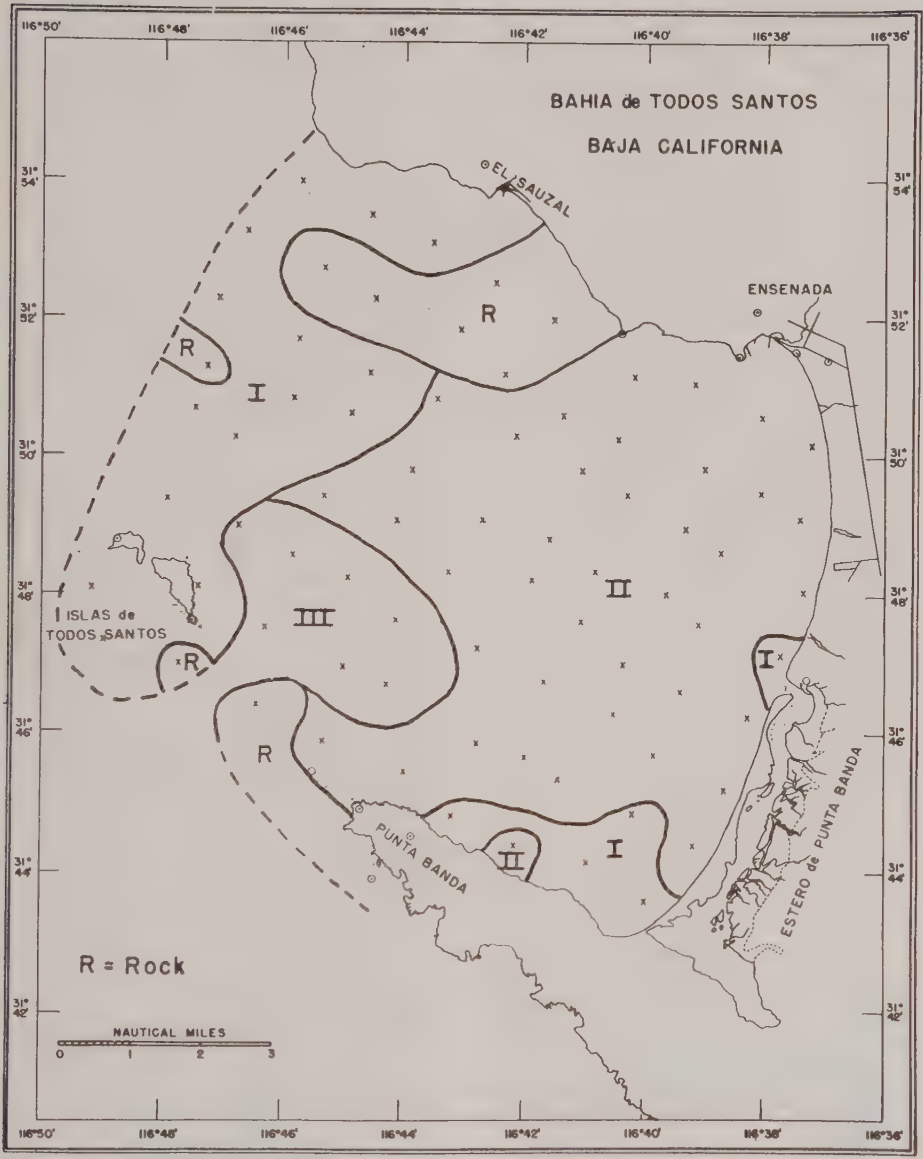


Text-fig. 5—Sediment groups in Todos Santos Bay based on plot of Phi median (Mdφ) against Phi deviation (σφ) and Phi skewness (αφ).

are well-sorted with the phi deviations generally below 0.50φ and there is little skewness. These fine sands and silts are grey in color and consist of angular quartz grains, with small percentages of dark minerals. The mica concentration generally increases offshore. The sediments generally contain little or no organic remains other than Foraminifera.

The Group III sediments occur just seaward of the Group II sediments over a depth range from 100 to 200 fathoms. Their medians are greater than 5φ, they are poorly sorted (phi deviations greater than 1φ), and they are generally skewed toward the finer sizes. They contain few organic remains other than Foraminifera. They have a high mica content and show signs of intense reworking by detritus-feeding organisms, principally worms. Careful washing of these samples produced large concentrations of fecal pellets in the coarser size fractions.

No sediment samples were obtained from


BAHIA de TODOS SANTOS
BAJA CALIFORNIA
EL SAUZAL
ENSENADA
ISLAS de TODOS SANTOS
PUNTA BANDA
ESTERO de PUNTA BANDA
R
I
II
III
R = Rock
NAUTICAL MILES
0
1
2
3
116°50'
116°48'
116°46'
116°44'
116°42'
116°40'
116°38'
116°36'
31° 54'
31° 52'
31° 50'
31° 48'
31° 46'
31° 44'
31° 42'

TEXT-FIG. 6—Areal distribution of sediment groups in Todos Santos Bay.

stations within the areas denoted by "R" in Text-figure 6. From stations B-100, B-101, and B-106 only pebbles and cobbles of sandstone, tuffs, and agglomerates encrusted with living organisms were obtained. No samples were obtained in numerous attempts at stations B-40, B-41, B-62, and B-107. A coarse brown sandstone was cored in place at stations B-98 and B-99. These rock samples contained no fossils. The areal extent of this submarine sandstone outcrop is not known, but some of the pebbles and cobbles from stations B-100, B-101, and B-106 have a similar lithology.

SOURCE OF BAY SEDIMENTS

The only exposures of pre-Recent sediments along the coast of this area are the Upper Cretaceous sandstones, limestone, and conglomerates (Chico) on the north side of Punta Banda, the sandstone and conglomerate formation (Trabuco ?) on the north Todos Santos Island and Punta Banda, and the Upper Miocene (Comondú) agglomerates, tuffs, and sandstones along the north shore of the mainland.

There is no continuous supply of sediment being brought into the bay by freshwater drainage at the present time. Streams flow into the bay at El Sauzal, Ensenada, and the mouth of the Estero de Punta Banda and into the estero along the base of Punta Banda. The rivers at El Sauzal and Ensenada flow intermittently all year, but the other stream valleys are dry except during the rainy season. During the winter months occasional heavy rains flood the usually dry stream beds and contribute considerable sediment to the bay.

The stream at El Sauzal drains the area of Cretaceous and pre-Cretaceous crystallines of the mountains to the north and flows several miles through the agglomerates, tuffs, sandstones, and volcanics of the Comondú formation. The rivers flowing into the bay from the east also originate in the Cretaceous and pre-Cretaceous rocks of the mountains but flow through extensive areas of Quaternary alluvium. The erosion of the crystallines of Punta Banda undoubtedly contributes considerable sediment to the estero, as can be seen from the freshly-eroded appearance of the coarse brown sands near its head.

DISCUSSION

The sediments of Group II in the inner part of the bay appear to be derived from the normal processes of stream erosion of the highlands and the extensive deposits of alluvium lying to the north and east of the bay. The present supply of sediments does not appear to be very great, and it is possible that some of the Group II sediments were derived from a previous cycle of heavier rainfall and subsequently distributed by marine processes.

The sediments of Group III appear to be the normal seaward extension of the Group II sediments. There is a decrease in grain size, they become more poorly sorted, and there is an increased skewness toward the finer sizes offshore; these factors are gradational between the two groups. The boundary between these groups is not sharp and is of necessity generalized, but it corresponds approximately with the 100-fathom contour.

Emery (1952) has recognized several types of sediments off the coast of southern California. Emery states (op. cit., p. 1107):

> "When sediments of authigenic, organic, residual, and relict origin are recognized and only the remaining detrital sediments are considered, the detrital sediments present a general trend of decreasing grain size in a seaward direction for the shelf off southern California."

He has recognized sediments similar to the present Group I sediments from Santa Monica Bay, San Pedro Bay, and off San Diego. A detailed study of the sediments off San Diego (Emery, Butcher, Gould, & Shepard, 1952) points out the complex sediment distributions that are encountered as a result of the mixing of sediment types other than detrital.

The characteristics of the Group I sediments, their geographic and bathymetric position, and the relationship to the other sedimentary groups indicate that they are not in adjustment with the present environment. The faunal data presented in a later section substantiate this conclusion.

The largest area of Group I sediments from the Todos Santos Islands to the mainland on the north side of the bay is complex and difficult to explain in terms of the present environment. The depth of water in which they occur, the presence of glauconite, the abundant organic remains, the presence of pebbles and cobbles encrusted with living organisms, and their geographic position suggest a source or sources other than those supplying sediment to the area at the present time. As with the other boundaries, there is no sharp contact between this group and the adjacent groups. The transition on the bay side is gradual with no apparent change in topography except to the east and south of the south Todos Santos Island, where the narrow insular shelf terminates in the steep walls of the deep channel. The presence of well-rounded pebbles and cobbles over most of this area suggests that it was, at some time in the past, subjected to the rigorous environment of the surf zone. There are no known physical agencies in the area at the present time that could account for such well-rounded pebbles and cobbles at the depth in which they occur. Also, the presence of living encrusting organisms on the pebbles and cobbles indicate that they are not at present undergoing any appreciable transportation or abrasion. The extremely high populations of dead Foraminifera and the presence of glauconite over the area suggest slow deposition.

It appears that this sediment is at least in part a result of vigorous abrasion by wave action at a time of lowered sea level. There are several possible sources of these sediments. The north Todos Santos Island is covered by a thick wedge of sandstones and conglomerates, and at least part of the bay area near El Sauzal is covered by submarine outcrops of a coarse brown sandstone. Subaerial and submarine weathering of these older sediments has undoubtedly contributed much of the coarse, sandy sediment found in the area. The well-rounded pebbles and cobbles of tuffs and agglomerates evidently originated in the hills to the north of the area. The continuous accumulation of foraminiferal shells and the lack of dilution by sediments has resulted in the large dead populations of Foraminifera.

The occurrence of Group I sediments at the mouth of the estero apparently is a result of the scouring action of the strong tidal currents which flow in and out of the estero. The nearshore drift in this part of the bay is to the north and it is suggested that the strong tidal currents, which reach velocities up to 2 knots, keep the area in the immediate vicinity of station B-73 free of finer sediments.

The sediments along Punta Banda reflect the influence of the poorly-consolidated Cretaceous sandstones which form precipitous cliffs along Punta Banda. The narrow beaches at the foot of the cliffs are littered with material that has been eroded back by an encroaching sea leaving a residual sediment near shore. There is no sharp contact or topographic change between these sediments and the adjacent Group II sediments. These sediments along Punta Banda apparently result from subaerial and possibly submarine erosion of the Cretaceous strata.

The importance of recognizing these relict or residual sediments cannot be over-emphasized. The presence of such sediments on the continental shelf, particularly off southern California and Mexico, indicates that large areas of the shelf are not in equilibrium with the present environmental conditions. The geological importance of such sediment types in the reconstruction of ancient environments is obvious. They must be recognized and separated from normal sediment distributions in order to establish useful principles of distribution for Recent sediments.

In summary, the sediments of Todos Santos Bay appear to be the result of two different environments of deposition. Group I sediments constitute an "unconformable" surface which appears to be the result of a past lowering of sea level. Group II and Group III sediments, which grade offshore from fine sands to silts and clays, appear to reflect the present environments of deposition in which they are found. The sediments reflecting the present environments appear to be transgressively overlapping the older sediments of Group I; but due to the limited supply of new sediments to the area at the present time, they have not succeeded in masking the old erosion surface. (Faunal evidence of the preceding conclusions is given on following pages.) The contamination of the Recent sediments by subaerial and submarine outcrops of "fossil" sediments is well-demonstrated by the surface sediments near the Cretaceous strata along Punta Banda. The sediments of Group I are complex in origin and contain residual sediments from the reworking of older strata, relict sediments from a previous lowering of sea level, abundant organic remains from the steady accretion of foraminiferal shells, and elements of Recent sediments. The recognition of residual, relict, and "fossil" sediments as "contaminants" of the "Recent" sediments is essential in establishing principles of distribution of sediments which reflect present environments.

BENTHONIC FORAMINIFERAL FAUNAS

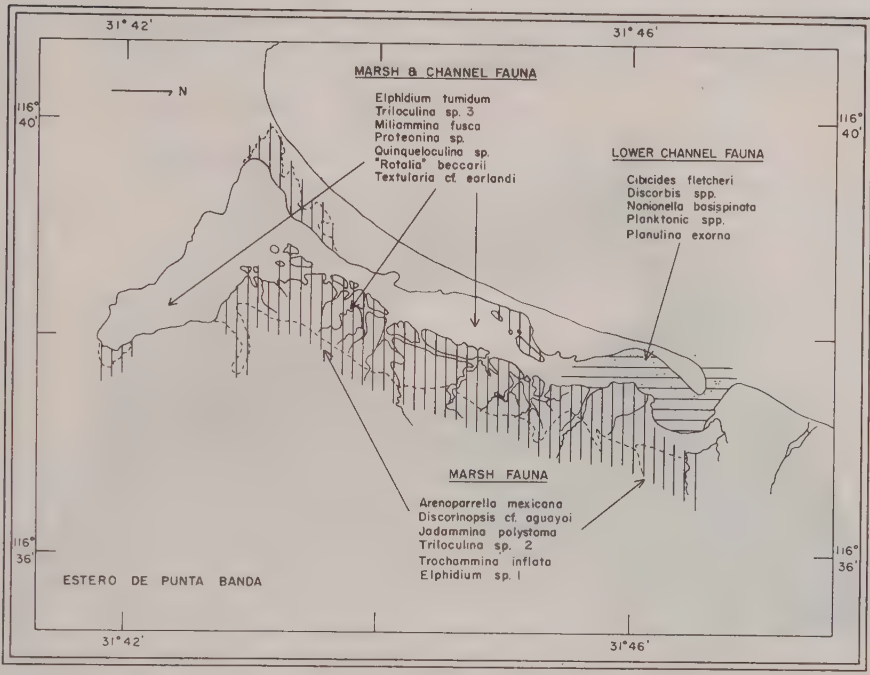
The benthonic Foraminifera of Todos Santos Bay can be divided into two well-defined groups: (1) the Estero de Punta Banda fauna and (2) the bay-open ocean fauna. These groups represent the two major environments of the area and reflect the differing physical, chemical, and biological controls of each environment. Each of these groups can be further divided into assemblages or "biofacies" within the two major environments.

ESTERO DE PUNTA BANDA FAUNA

The estero fauna consists of species which are restricted to a lagoon and marsh environment and also some species which

TABLE 6—OCCURRENCES OF LIVING AND TOTAL BENTHONIC FORAMINIFERA IN ACTUAL NUMBERS IN THE ESTERO DE PUNTA BANDA (PER UNIFORM SIZE SAMPLE).

LOCATION	MARSH													CHANNEL																			
STATION	E 4	E 7	E 10	E 11	E 14	E 15	E 16	E 26	E 27	E 28	E 29	E 30	E 31	E 1	E 2	E 3	E 5	E 6	E 8	E 9	E 12	E 13	E 17	E 18	E 19	E 20	E 21	E 22	E 23	E 24	E 25	E 32	E 33
DEPTH	I.T.	0'6"	I.T.	I.T.	I.T.	I.T.	I.T.	I.T.	I.T.	1'0"	I.T.	I.T.	I.T.	I.T.	I.T.	5'0"	6'6"	3'0"	2'0"	2'0"	2'0"	5'0"	6'0"	I.T.	5'0"	I.T.	5'0"	1'0"	1'0"	1'6"	I.T.	1'0"	I.T.
TOTAL LIVING POPULATION	0	40	40	108	10	4	0	0	26	30	0	0	0	14	20	6	12	108	6	0	8	20	0	0	104	0	0	0	0	2	0	0	64
Arenoparrella mexicana		2	4																														
Cibicides fletcheri														10																2			
Discorbis spp.														4							6												
Elphidium spinatum																																	
E. tumidum		2													14	6		64	4														60
E sp 1			4	4		4																											
Jadammina polystoma		6	6	10					2																								
Miliammina fusca				74						10					6		2	2			2	20											2
Proteonina sp.		30	26	20													10	42															
Quinqueloculina sp.																			2						2								
"Rotalia" beccarii																																	2
Triloculina sp. 2									4	20																							
T. sp. 3																									102								
Trochammina inflata					10				20																								
TOTAL DEAD POPULATION	20	84	80	140	108	10	18	28	288	178	2	40	134	16	36	81	28	158	30	62	34	62	3	0	215	22	33	6	36	10	96	6	140
Angulogerina angulosa																															6		
Arenoparrella mexicana		8	10		28	2							32						6	10					6								2
Buliminella bassendorfensis																						22			30		2		6		38		
Cibicides fletcheri														12	4											20	26	6	16	8	14		
Discorbis spp.														4							6				4		2		2		4		
Discorinopsis aguayoi	2							8		2																							
Elphidium spinatum																2																	
E. translucens																									10	2					4		
E. tumidum		2											12		24	46		80	8	28	6	8	2		30		1						76
E. sp.			4	20		4	2			68	2							10											6	2	5		
Jadammina polystoma	8	20	6	22			4	12	38			2	2							2													4
Lamellodiscorbis sp.																																	20
Miliammina fusca		16	24	74			2	2		36			66		6		2	2			14	20											10
Nonionella basispinata																									2		2		2		6		
Planulina exorna																															2		
Proteonina sp.		30	26	20													10	42															
Quinqueloculina sp.															2				2						12								
Reophax sp. 2						2										12	8	18	8	4	2	4									2		
"Rotalia" beccarii							2						6			8				8					2				4		14	2	4
Textularia cf. earlandi							2						2			10	8	6		2		8											2
Triloculina sp. 2									32	60		38																					
T. sp. 3																									118								
Trochammina inflata	10	8	10	4	80	2	6	6	218	12			14						6	8	6											4	22
Planktonic forms																3							1		1						1		


31° 42'
31° 46'
N
116° 40'
116° 40'
MARSH & CHANNEL FAUNA
Elphidium tumidum
Triloculina sp. 3
Miliammina fusca
Proteonina sp.
Quinqueloculina sp.
"Rotalia" beccarii
Textularia cf. earlandi
LOWER CHANNEL FAUNA
Cibicides fletcheri
Discorbis spp.
Nonionella basispinata
Planktonic spp.
Planulina exorna
MARSH FAUNA
Arenoparrella mexicana
Discorinopsis cf. aguayoi
Jadammina polystoma
Triloculina sp. 2
Trochammina inflata
Elphidium sp. 1
116° 36'
116° 36'
ESTERO DE PUNTA BANDA
31° 42'
31° 46'

TEXT-FIG. 7—Foraminiferal faunas in the Estero de Punta Banda.

are most common in the bay environment. Undoubtedly, some of the latter are able to live in both environments whereas others appear to be contaminants from the bay. The distribution of the foraminiferal species is presented in Table 6. The distribution of the faunas in the Estero de Punta Banda is shown in Text-figure 7.

Marsh facies.—The species characteristic of the marsh facies are perhaps the most distinctive; the living representatives are restricted to the intertidal area covered by marsh grasses, *Salicornia pacifica* and *Spartina leiantha.*

The following species are representative of the inter-tidal areas of marsh grasses:

Arenoparrella mexicana (Kornfeld)
Discorinopsis cf. *D. aguayoi* (Bermudez)
Elphidium sp.
Jadammina polystoma Bartenstein and Brand
Triloculina sp. 2
Trochammina inflata (Montagu)

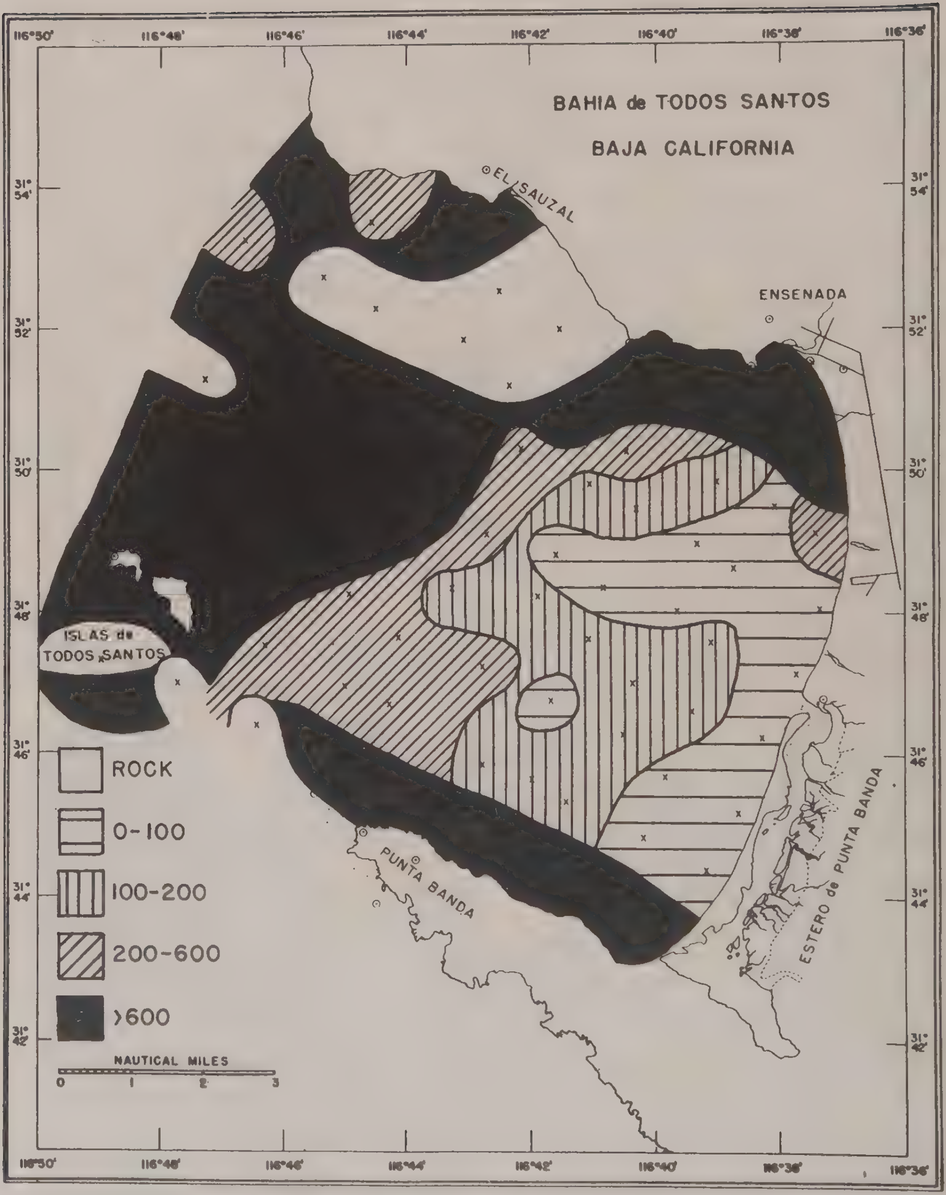
The distribution of the dead specimens of these species does not coincide with the living distributions in all cases. Dead specimens are common in the channels and on the inter-tidal sand flats.

Lower channel facies.—The lower channel fauna appears to reflect the influence of the bay environment. The species are common in the bay and some undoubtedly are contaminants from the bay. They only occur living at or near the mouth of the estero, in the channel, and on the inter-tidal sand flats. The lower channel fauna is characterized by the following species:

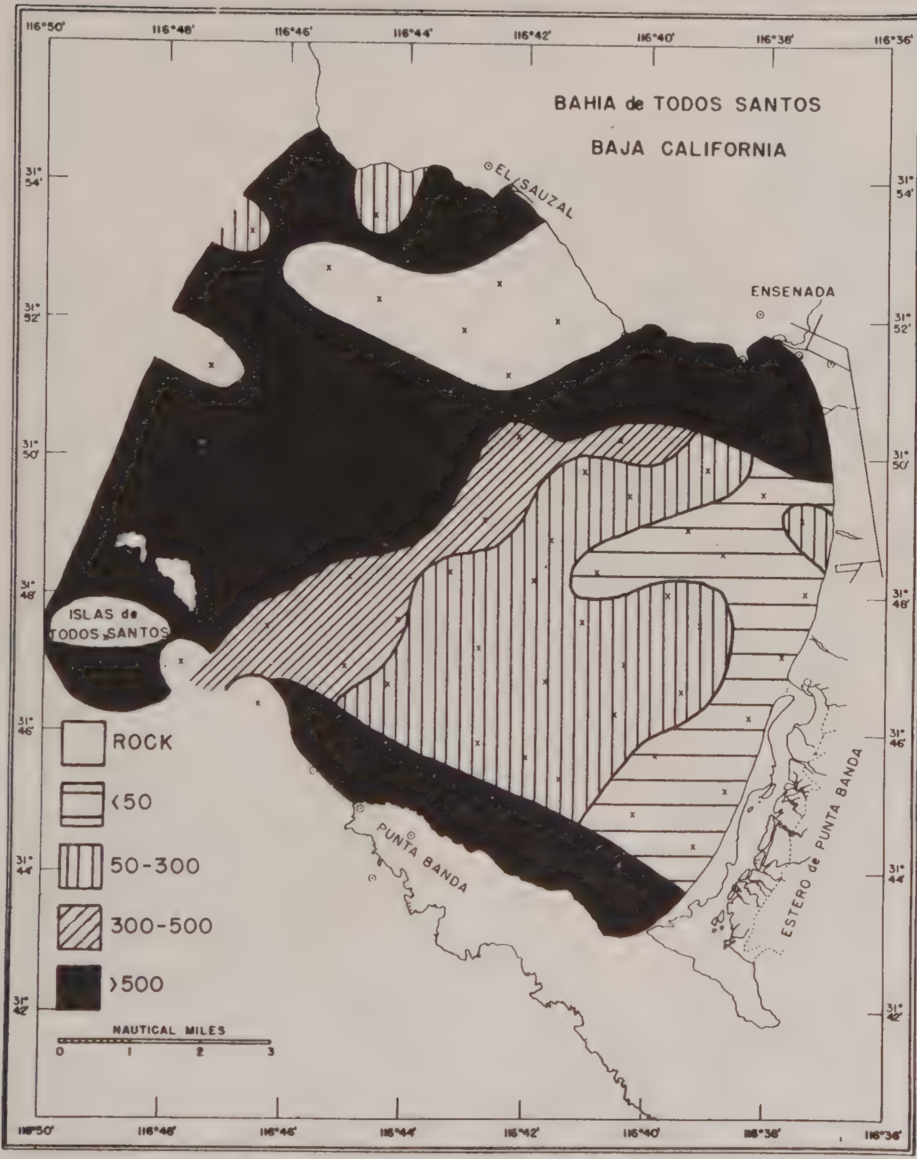
Cibicides fletcheri Galloway & Wissler
Discorbis spp.
Nonionella basispinata (Cushman & Moyer)

A few specimens of planktonic species are found in this fauna.

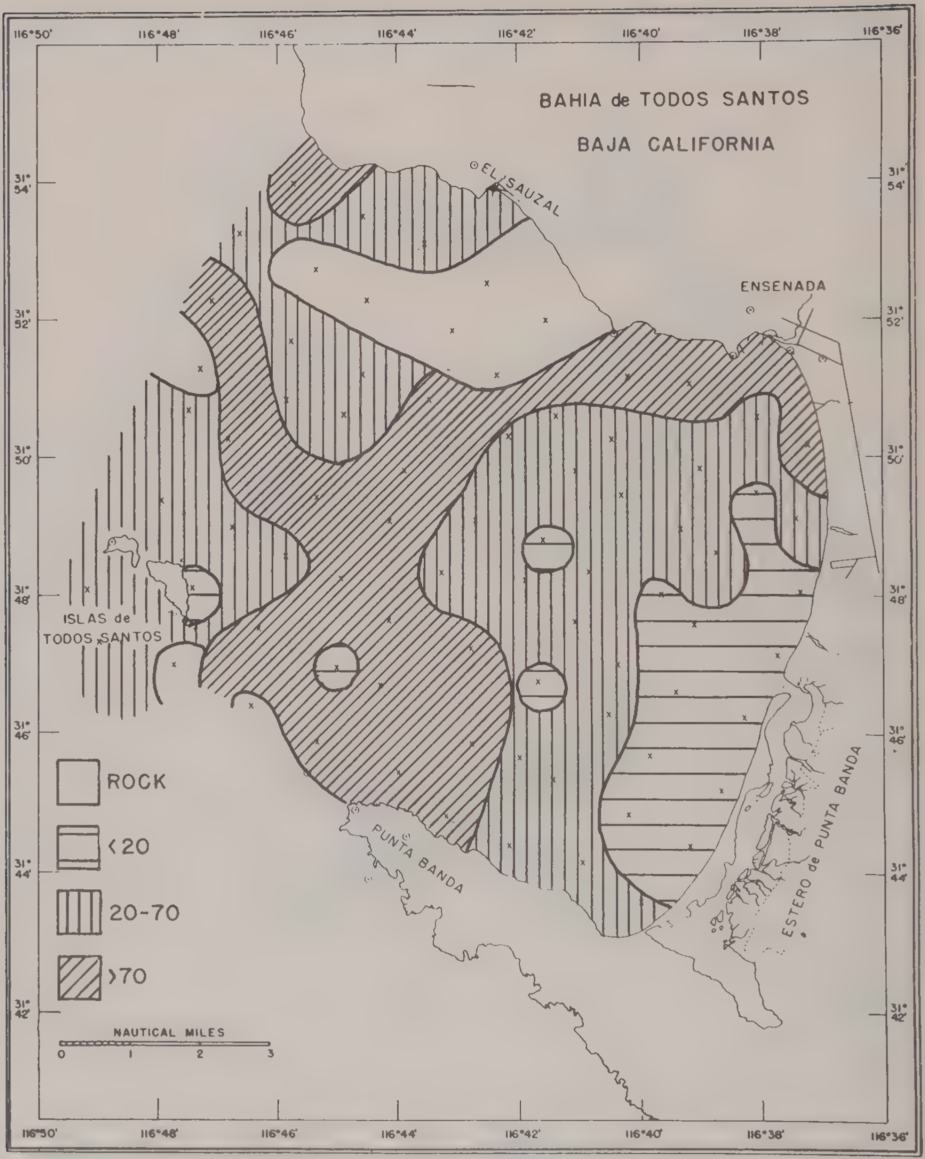
Mixed channel and marsh facies.—Some species are common both in the channels and inter-tidal flats and in the marsh areas. *Elphidium tumidum* Natland, *Miliammina fusca* (H. B. Brady), and *Proteonina* sp. occur in both of these environments. *Quinqueloculina* sp., *Triloculina* sp. 3, and "*Rotalia*" cf. "*R.*" *beccarii* (Linné) are found


BAHIA de TODOS SANTOS
BAJA CALIFORNIA
EL SAUZAL
ENSENADA
ISLAS de TODOS SANTOS
PUNTA BANDA
ESTERO de PUNTA BANDA
ROCK
0-100
100-200
200-600
>600
NAUTICAL MILES
0
1
2
3
116°50'
116°48'
116°46'
116°44'
116°42'
116°40'
116°38'
116°36'
31° 54'
31° 52'
31° 50'
31° 48'
31° 46'
31° 44'
31° 42'

TEXT-FIG. *8*—Distribution of total (living and dead) populations of benthonic Foraminifera in Todos Santos Bay in number of specimens per sample.


116°50'
116°48'
116°46'
116°44'
116°42'
116°40'
116°38'
116°36'
BAHIA de TODOS SANTOS
BAJA CALIFORNIA
31° 54'
EL SAUZAL
31° 52'
ENSENADA
31° 50'
31° 48'
ISLAS de TODOS SANTOS
31° 46'
ROCK
<50
50-300
300-500
>500
PUNTA BANDA
ESTERO de PUNTA BANDA
31° 44'
31° 42'
NAUTICAL MILES
0
1
2
3

TEXT-FIG. 9—Areal distribution of dead benthonic Foraminifera in Todos Santos Bay in number of specimens per sample.


BAHIA de TODOS SANTOS
BAJA CALIFORNIA
EL SAUZAL
ENSENADA
ISLAS de TODOS SANTOS
PUNTA BANDA
ESTERO de PUNTA BANDA
ROCK
<20
20-70
>70
NAUTICAL MILES
0
1
2
3
116°50'
116°48'
116°46'
116°44'
116°42'
116°40'
116°38'
116°36'
31° 54'
31° 52'
31° 50'
31° 48'
31° 46'
31° 44'
31° 42'

TEXT-FIG. *10*—Areal distribution of living benthonic Foraminifera in Todos Santos Bay in number of specimens per sample.

living only in the channel and inter-tidal sand flat samples; the dead representatives of these species are not as restricted in their distribution as are the living specimens (Table 6). *Lamellodiscorbis* sp. was found at only one station in the estero (E-33). *Triloculina* sp. 3 was recorded only from Station E-19.

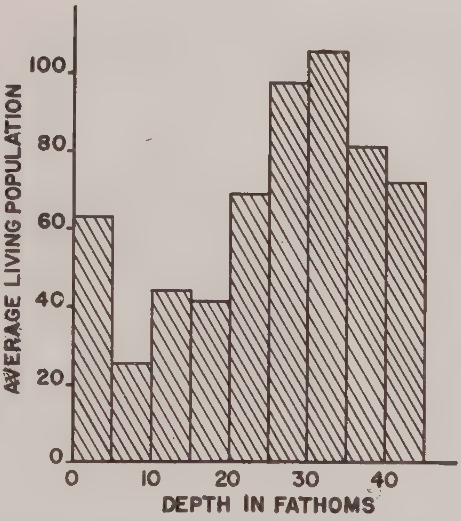
BAY FAUNA

Foraminiferal populations.—The distribution of total populations (living and dead) of benthonic Foraminifera in Todos Santos Bay is shown in Text-figure 8. The populations are small near the inside of the bay and generally increase with increasing depth. Unusually large populations occur along Punta Banda and between the Todos Santos Islands and the mainland to the northeast. The distributions of the dead populations (Text-fig. 9) are strikingly similar to the distributions of the total populations (living and dead). The living populations, however (Text-fig. 10), show different distributions from the dead and total populations. The frequency distribution of the average living populations per 5-fathom interval shows a marked maximum between 30 and 35 fathoms (Text-fig. 11). The frequency distribution of the dead populations per 5-fathom intervals is multimodal (Text-fig. 12). The high populations of dead Foraminifera do not correspond with the areas or depths of maximum production of living Foraminifera in the bay at the time of collection. A comparison of the variations in the total living and total dead populations shows striking differences. The total living populations vary between 0 and 229 specimens per sample. The total dead populations vary over the same area from 0 to more than 18,000 specimens per sample.

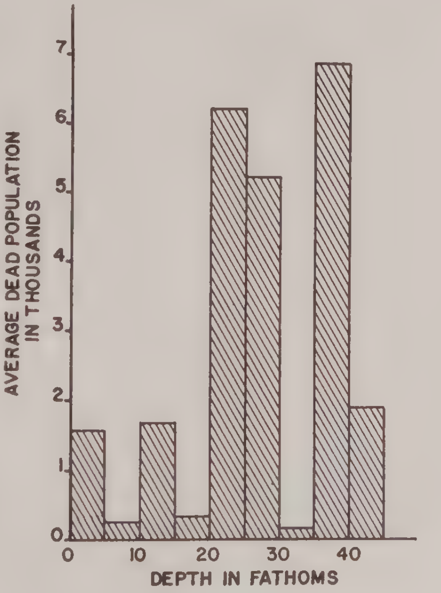
The sizes of populations of empty tests are primarily functions of: (1) rates of production of tests, (2) dilution of populations by detrital sediments, and (3) preservation of the empty tests.

In order to examine the relationship between the living and dead populations an "L/D" ratio has been established, as follows:

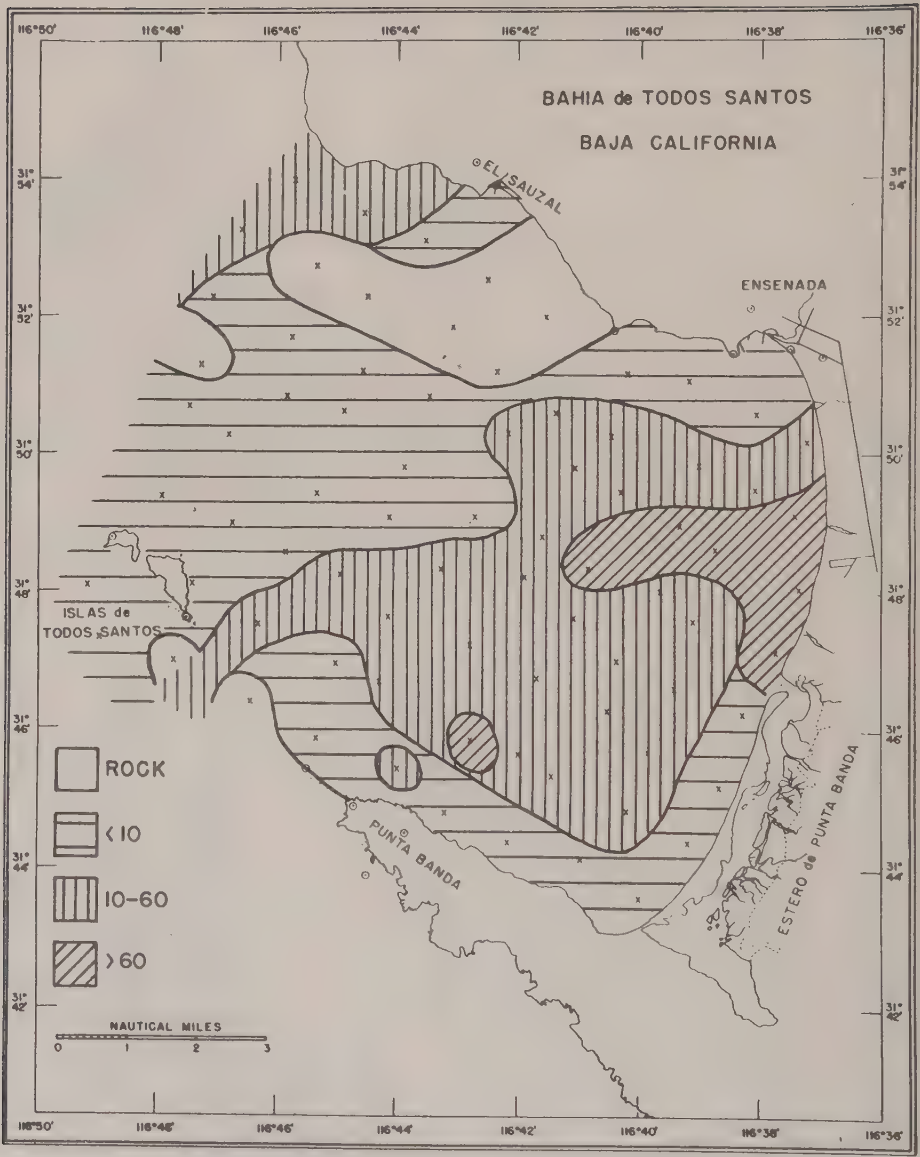
$$R = \frac{\text{living population}}{\text{dead population}} \times 100$$



TEXT-FIG. *11*—Depth distribution of average living populations of benthonic Foraminifera in Todos Santos Bay.



TEXT-FIG. *12*—Depth distribution of average dead populations of benthonic Foraminifera in Todos Santos Bay.


116°50'
116°48'
116°46'
116°44'
116°42'
116°40'
116°38'
116°36'
31° 54'
31° 52'
31° 50'
31° 48'
31° 46'
31° 44'
31° 42'
BAHIA de TODOS SANTOS
BAJA CALIFORNIA
EL SAUZAL
ENSENADA
ISLAS de TODOS SANTOS
PUNTA BANDA
ESTERO de PUNTA BANDA
ROCK
< 10
10-60
> 60
NAUTICAL MILES
0
1
2
3

TEXT-FIG. *13*—Areal distribution of L/D ratios in Todos Santos Bay.

This ratio varies from less than 1 to more than 100 in Todos Santos Bay, as shown in Text-figure 13 and Table 7. A comparison of the areal plot of the L/D ratios (Text-fig. 13) with the total dead populations (Text-fig. 9) and the total living populations (Text-fig. 10) demonstrates that the L/D ratios vary according to dead populations and are less influenced by the relatively smaller variations in the living populations.

TABLE 7.—TOTAL LIVING AND DEAD POPULATIONS AND L/D RATIOS FOR TODOS SANTOS BAY SAMPLES

Sta. No.	Depth (fms.)	Living	Dead	L/D ×100
B-34	3	63	1,154	5.5
B-35	8	24	673	3.6
B-36	19	64	548	11.3
B-37	25	105	1,610	6.5
B-38	35	140	579	24.2
B-39	68	104	973	10.7
B-42	39	23	13,218	.2
B-43	40	46	12,520	.4
B-44	25	14	7,264	.2
B-45	141	98	506	19.4
B-46	150	16	256	6.3
B-47	108	80	215	37.2
B-48	30	91	82	111.0
B-49	28	44	73	60.0
B-50	20	65	162	40.1
B-51	12	1	4	25.0
B-52	6	—	—	—
B-53	7	—	—	—
B-54	11	5	19	26.3
B-55	18	63	121	52.0
B-56	24	13	55	23.6
B-57	31	121	257	47.1
B-58	96	144	382	37.6
B-59	110	88	413	21.3
B-60	110	42	892	4.7
B-61	92	40	1,087	3.7
B-62	23	52	771	6.8
B-63	22	61	11,632	.5
B-64	24	148	13,296	1.1
B-65	28	229	12,960	2.0
B-66	27	105	1,370	7.7
B-67	24	62	126	49.2
B-68	19	42	153	27.4
B-69	19	32	109	29.4
B-70	17	27	114	23.7
B-71	12	19	141	13.5
B-72	5	—	3	—
B-73	5	24	38	63.2
B-74	12	18	125	14.4
B-75	15	17	59	28.8
B-76	16	21	22	95.5
B-77	16	8	85	7.1
B-78	17	22	311	7.1
B-79	20	93	903	10.3
B-80	22	44	3,501	1.3
B-81	22	40	10,088	.4
B-83	26	124	12,936	1.0
B-84	22	66	18,592	.4
B-85	20	69	6,624	1.0
B-86	20	115	8,702	1.3
B-87	12	63	314	20.1
B-88	16	57	94	60.1
B-89	15	32	86	37.2
B-90	13	37	44	84.1
B-91	11	22	20	109.0
B-92	6	3	2	150.0
B-93	6	57	184	67.9
B-94	10	13	23	56.5
B-95	13	36	149	24.2
B-96	15	44	391	11.5
B-97	15	23	1,621	13.8
B-102	26	60	202	29.7
B-103	19	134	649	20.6
B-104	13	34	168	22.2
B-105	12	63	2,304	2.7
B-108	11	136	12,104	1.1
B-109	10	126	6,632	1.9
B-110	8	45	569	7.9
B-111	6	75	594	12.6
B-116	153	16	376	42.5
B-118	275	137	638	21.5

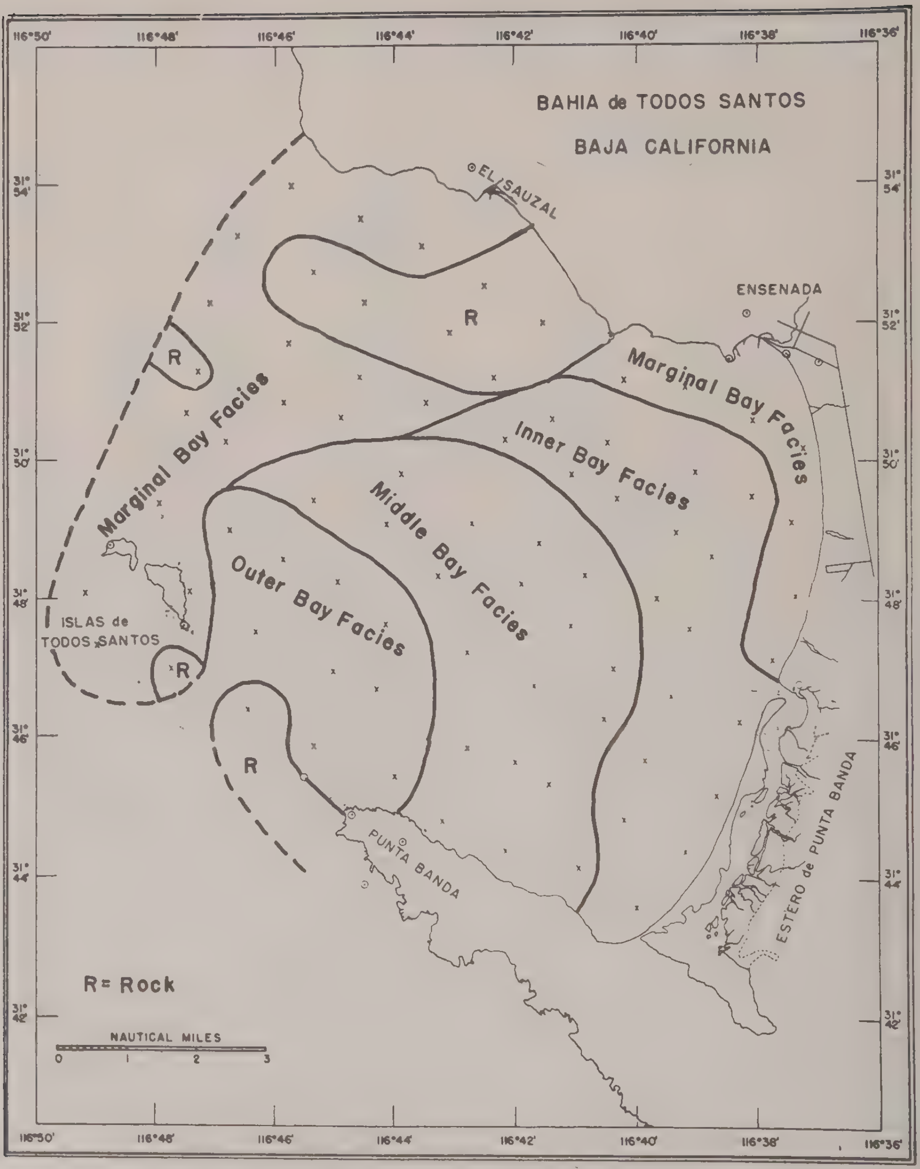
The living representatives of the benthonic foraminiferal species in Todos Santos Bay generally fit into four areal assemblages. The boundaries of these assemblages are generalized but the species associated with each assemblage occur most abundantly within the areas outlined in Text-figure 14.

Outer bay facies.—The following group of species is restricted to the deeper part of the bay and the deep channel between Punta Banda and the Todos Santos Islands:

Reophax gracilis (Kiaer)
Uvigerina peregrina Cushman vars.
Recurvoides spp.
Chilostomella ovoidea Reuss
Bolivina acuminata Natland
B. pacifica Cushman & McCulloch
Bulimina denudata Cushman & Parker
Globobulimina spp.

Middle bay facies.—A second assemblage has an areal distribution generally marginal to the deep depression in the center of the bay. The species are:

Goësella flintii Cushman
Reophax curtus Cushman
Proteonina sp.
Ammotium planissimum (Cushman)
Labrospira cf. *L. advena* (Cushman)
Reophax scorpiurus Montfort


BAHIA de TODOS SANTOS
BAJA CALIFORNIA
EL SAUZAL
ENSENADA
Marginal Bay Facies
Marginal Bay Facies
Inner Bay Facies
Middle Bay Facies
Outer Bay Facies
ISLAS de TODOS SANTOS
PUNTA BANDA
ESTERO de PUNTA BANDA
R
R
R
R
R= Rock
NAUTICAL MILES
0
1
2
3
116°50'
116°48'
116°46'
116°44'
116°42'
116°40'
116°38'
116°36'
31° 54'
31° 52'
31° 50'
31° 48'
31° 46'
31° 44'
31° 42'

TEXT-FIG. *14*—Benthonic Foraminiferal facies in Todos Santos Bay.

Inner bay facies.—A third group of species is most abundant in the inner part of the bay, but generally occurs over the entire bay area. The group includes the following species:

Nonionella miocenica stella Cushman & Moyer
Proteonina atlantica Cushman
Nonionella basispinata (Cushman & Moyer)
Discorbis spp.
Labrospira cf. *L. columbiensis* (Cushman)
Trochammina pacifica Cushman
Eggerella advena (Cushman)
Quinqueloculina sp.
Elphidium translucens Natland
Buliminella elegantissima (d'Orbigny)

Marginal bay facies.—The species of this assemblage generally are distributed over the area of relatively shallow water between the islands and the mainland on the northeast, and the areas immediately adjacent to the mainland and Punta Banda. This group includes the following species:

Angulogerina angulosa (Williamson)
Cassidulina subglobosa H. B. Brady
Cibicides fletcheri Galloway & Wissler
Cibicidina nitidula Bandy
Elphidium tumidum Natland
"*Rotalia*" spp.
Bolivina striatella Cushman
Textularia cf. *T. schenchi* Cushman & Valentine
Gaudryina cf. *G. subglabrata* Cushman & McCulloch
Bolivina vaughani Natland
Bifarina hancocki Cushman & McCulloch
Planulina exorna Phleger & Parker

Several species of Foraminifera were identified from Todos Santos Bay for which no living representatives were found. These are the following:

Elphidium crispum (Linné)
Eponides cf. *E. repandus* (Fichtel & Moll)
Astrononion stellatum (Cushman & Edwards)
Rudigaudryina inepta Cushman & McCulloch
Rupertia cf. *R. stabilis* Wallich
Bolivina cf. *B. pseudoplicata* Heron-Allen & Earland
Cassidulina californica Cushman & Hughes
Sigmoilina cf. *S. miocenica* Cushman
Various Miliolidae

FORAMINIFERAL ASSEMBLAGES IN OFFSHORE TRAVERSE

Composition of the offshore fauna.—The benthonic foraminiferal faunas of the offshore traverse belong to the bay-open ocean fauna. This assemblage generally occurs outside the immediate area of Todos Santos Bay and extends to depths of at least 600 fathoms. It is characterized by the following species:

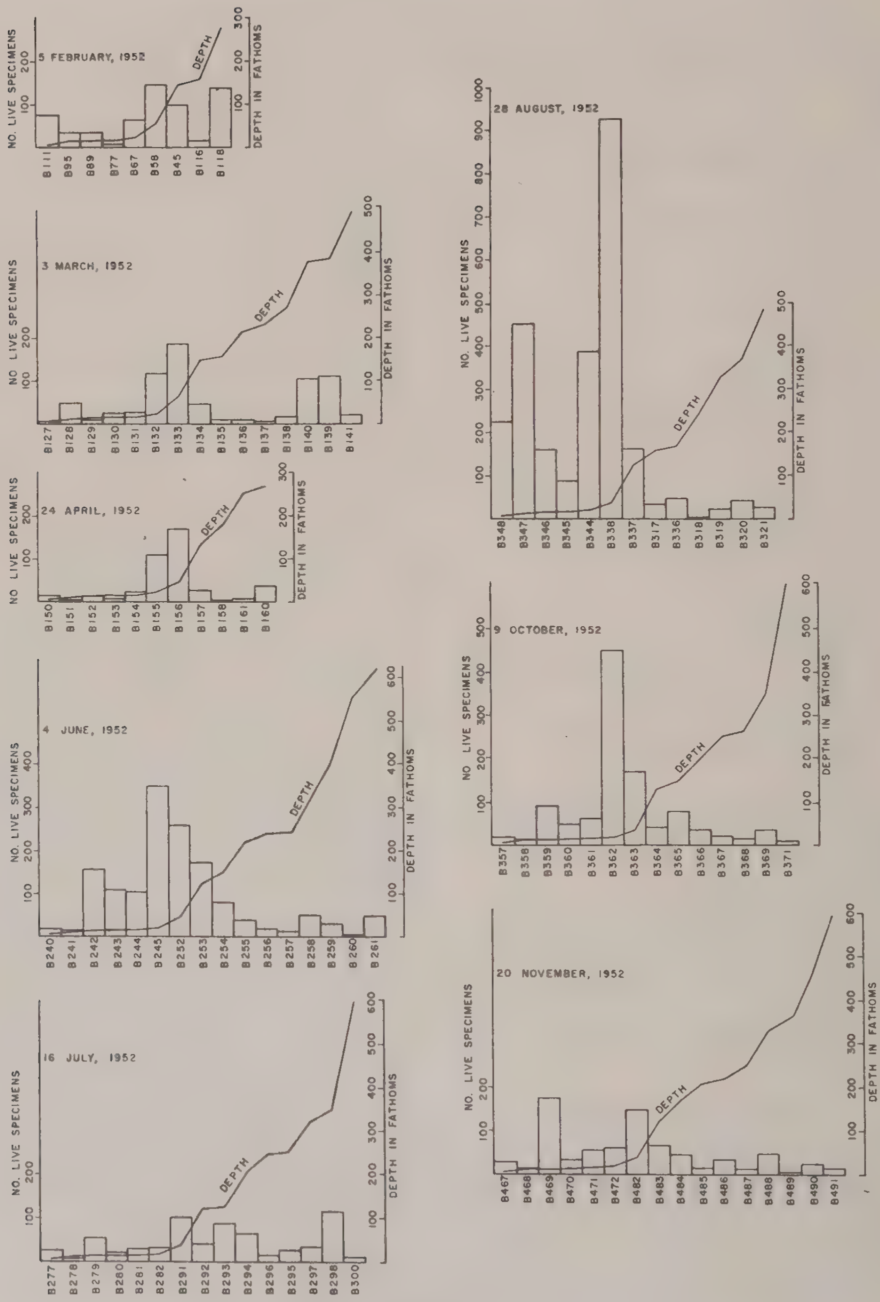
Cancris auricula (Fichtel & Moll)
Valvulineria araucana (d'Orbigny)
V. inequalis (d'Orbigny)
Bolivina argentea Cushman
B. spissa Cushman
B. minuta Natland
Cassidulina delicata Cushman
C. laevigata d'Orbigny
Bulimina exilis tenuata (Cushman)
Virgulina bramletti Galloway & Morrey
V. seminuda Natland
Reophax horrida Cushman
R. sp. 1
Proteonina sp.
Epistominella smithi (Stewart & Stewart)
Loxostomum pseudobeyrichi (Cushman)
Höglundina elegans (d'Orbigny)

As in the bay, the dead populations of the above species differ from the living ones in size and distribution. The dead specimens generally are much more common and occur through a greater depth range than the live specimens.

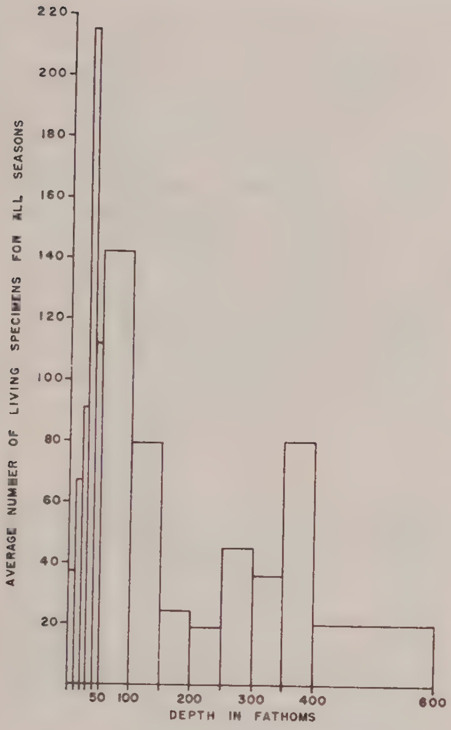
Living populations in seasonal samples.—Only living population counts were made from the seasonal samples. Histograms of the total living populations at each station for the eight seasonal collections are presented in Text-figure 15. A depth curve is plotted with each histogram for comparative purposes.

The seasonal histograms show two distinct variations in the living populations, a depth variation along the traverse and a seasonal variation. The average number of living specimens in all samples plotted against depth shows three distinct maxima (Text-fig. 16). The first maximum is at 30 to 40 fathoms. This is the most marked of the three maxima and the living populations average more than 200 specimens per sample at this depth. The second maximum occurs at 50 to 100 fathoms, and the samples have an average living population of 142 specimens. The third maximum occurs between 350 and 400 fathoms and averages 80 specimens per sample. It must be emphasized that this histogram of average living populations (Text-fig. 16) includes population counts from all seasons of the year and thus is influenced by seasonal variations.

Seasonal variations in living populations also are apparent in the seasonal traverse histograms (Text-fig. 15). The largest living



TEXT-FIG. *15*—Frequencies of living populations along seasonal traverses (per sample).



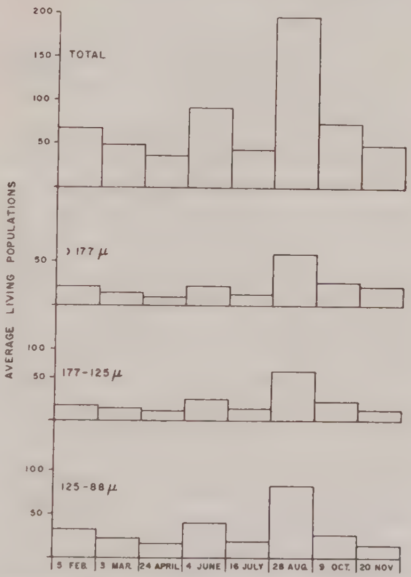
TEXT-FIG. *16*—Depth distribution of average living populations.

populations occurred in the August sampling with a smaller maximum in June. Seasonal variation is well-illustrated by a plot of the average living populations for each of the eight periods of collection (Text-fig. 17). This same illustration shows the relative abundances of living Foraminifera in the three size fractions from which population counts were made, with no appreciable differences in populations within different size fractions. Slightly larger populations occurred in the 125μ–88μ fraction at all seasons sampled except November. In November, the largest population occurred in the 177μ fraction.

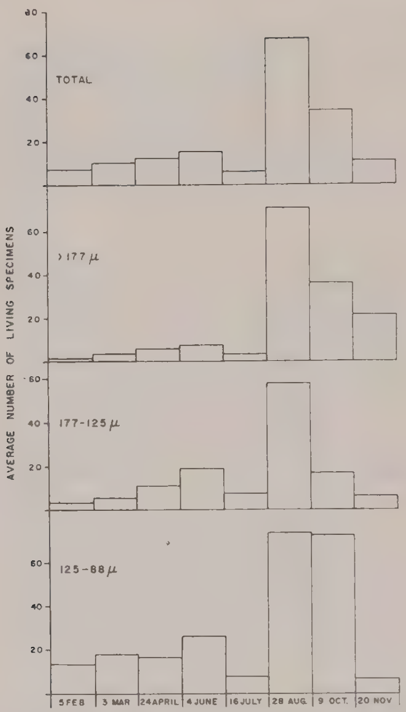
The seasonal variations in populations of individual species will affect the maximum and minimum populations shown in Text-figure 17. Seasonal distribution of *Nonionella miocenica stella* Cushman & Moyer in the total samples, and also the size fractions is shown in Text-figure 18. In this species there is also no appreciable difference in the size fraction populations, with slightly larger populations occurring in the 125–88μ fraction. This species was most abundant during August and is partly responsible for the maximum during that month. Other species show maxima during other seasons and contribute to fluctuations in the seasonal populations.

It is apparent that August is the month of maximum abundance of benthonic Foraminifera in this area. It also appears that each species has a discrete range over which it occurs. The frequency distributions of most of the species are represented in Text-figures 19–23.

Some species have very restricted depth ranges. *Quinqueloculina* sp., *Elphidium spinatum* Cushman & Valentine, *Miliammina fusca* (H. B. Brady), and *Textularia* cf. *T. earlandi* Parker (Text-figs. 19, 20) only occur over a depth range of 20 fathoms. *Elphidium translucens* Natland, *E. tumidum* Natland, *Gaudryina* cf. *G. subglabrata* Cushman & McCulloch, *Cibicidina nitidula* Bandy, and *Trochammina kellettae* Thal-



TEXT-FIG. *17*—Seasonal abundances of average living populations for total samples and size fractions.



TEXT-FIG. *18*—Seasonal abundance of *Nonionella miocenica stella* Cushman & Moyer; total samples and size fractions.

mann, etc. (Text-fig. 19) only occur over a depth range of 30 fathoms. These species, which have restricted depth ranges, all occur in water shallower than 40 fathoms.

A few species which are most abundant in water depths shallower than 50 fathoms apparently live over large depth ranges. *Labrospira* cf. *L. columbiensis* (Cushman) (Text-fig. 19) is most abundant shoaler than 50 fathoms but occurs to depths of 300 fathoms. *Goësella flintii* Cushman (Text-fig. 21) is most abundant between 40 and 50 fathoms, but occurs in depths of as much as 400 fathoms. Species which have frequency maxima shallower than 50 fathoms have fairly narrow depth ranges and are more skewed toward deep water. In contrast, species which have frequency maxima deeper than 100 fathoms have relatively wide depth ranges, but nevertheless tend to be skewed toward the deeper water.

Some of the frequency distributions show bimodal tendencies, as *Ammotium planissimum* (Cushman) (Text-fig. 21) and *Proteonina* sp. (Text-fig. 23). This fact suggests the possibility that more than one species was included in such plots.

Several species show patchy distributions. This tendency is most noticeable in forms that show a frequency maximum shallower than 50 fathoms and appears to be related to displacement of these shallow-water species into deeper water. Most of these anomalous occurrences are at or near the base of rugged submarine topography and appear to be displaced down slope along with shallow-water sediments. It is interesting to note that these shallow-water species are able to survive, possibly only temporarily, in deeper-water environments.

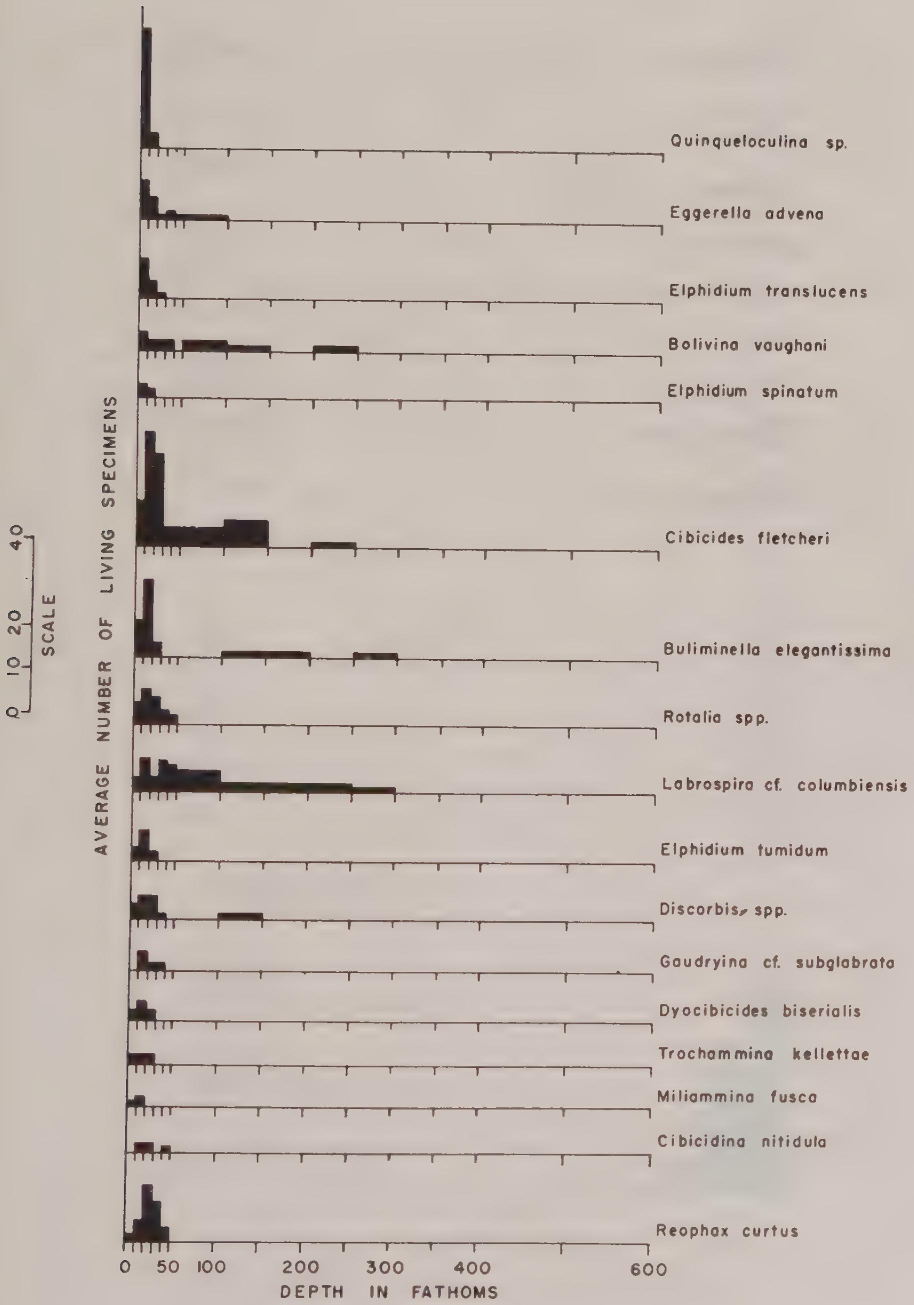
DEPTH FACIES

Four depth facies are recognizable within the bay and open-ocean fauna on the basis of the frequency distributions of living benthonic Foraminifera. These facies are bounded by distinct faunal boundaries and can be recognized easily from Text-figures 19–23. The upper boundary is at approximately 30 fathoms. Living specimens of the following species are restricted to depths of less than 30 fathoms:

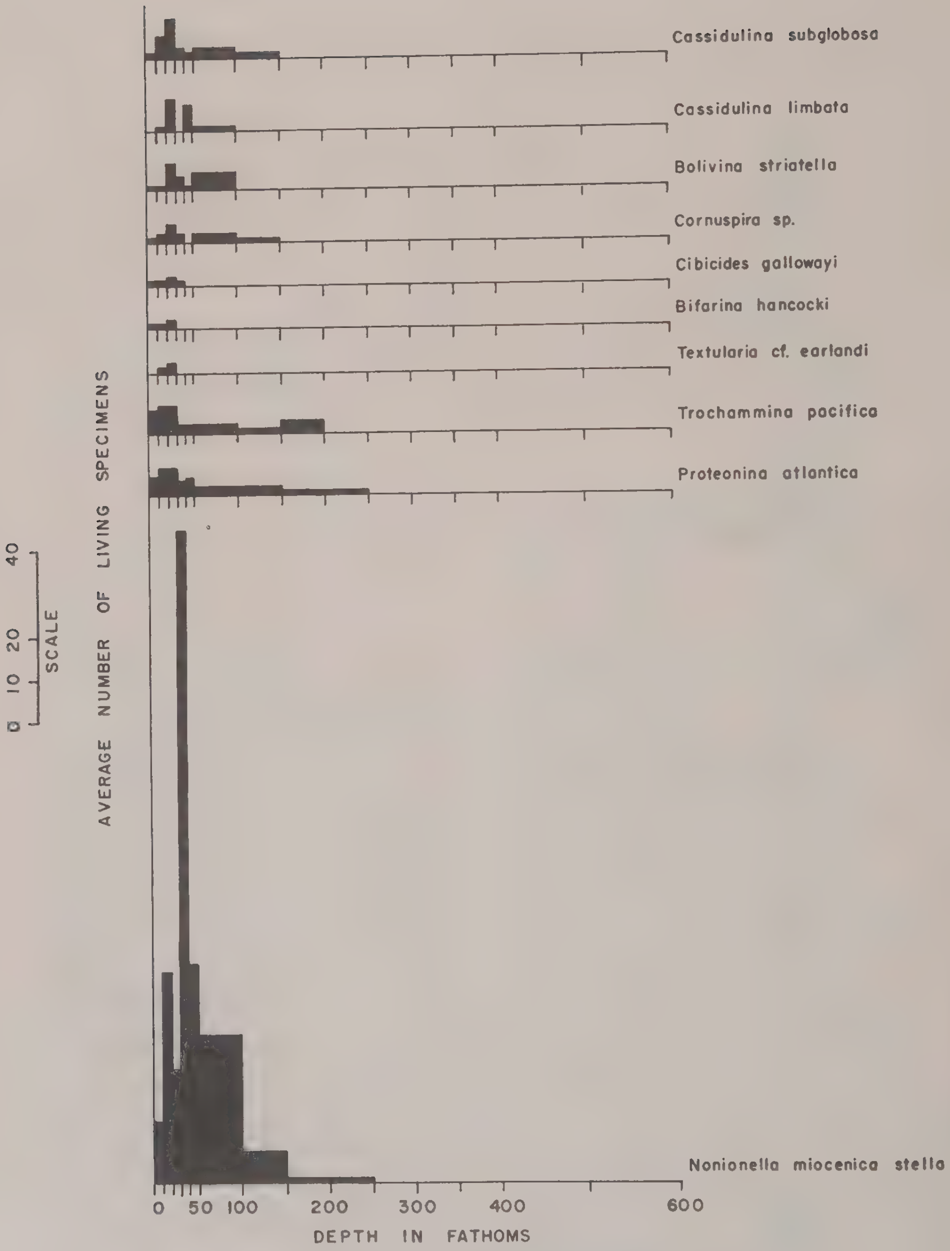
Quinqueloculina sp.
Elphidium translucens Natland
E. tumidum Natland
E. spinatum Cushman & Valentine
Dyocibicides biseralis Cushman & Valentine
Trochammina kellettae Thalmann
Miliammina fusca (H. B. Brady)
Bifarina hancocki Cushman & McCulloch
Textularia cf. *T. earlandi* Parker

The following species are most abundant above 30 fathoms but occur deeper:

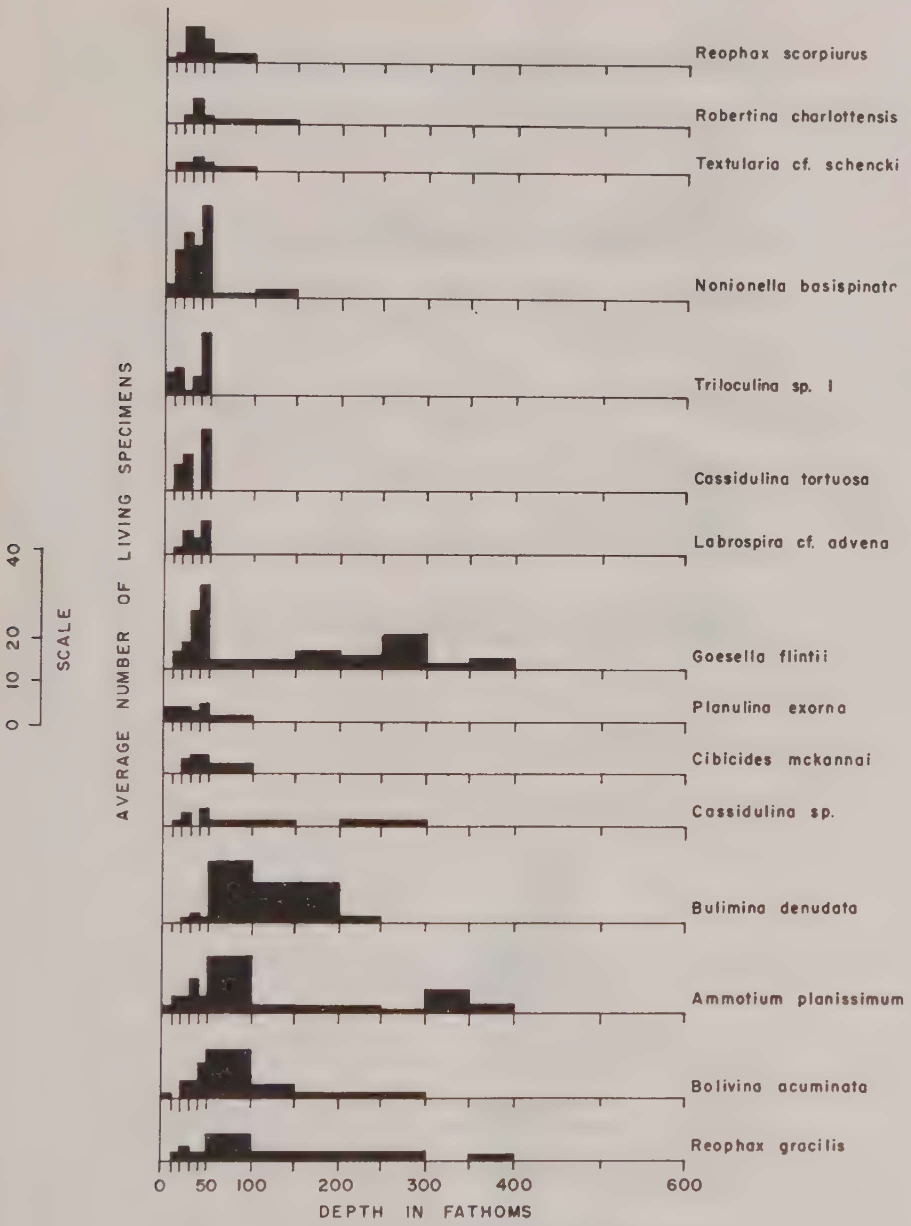
Eggerella advena (Cushman)
Bolivina vaughani Natland
Cibicides fletcheri Galloway & Wissler
Buliminella elegantissima (d'Orbigny)
"*Rotalia*" spp.
Labrospira cf. *L. columbiensis* (Cushman)
Discorbis spp.
Gaudryina cf. *G. subglabrata* Cushman & McCulloch
Reophax curtus Cushman
Cibicidina nitidula Bandy
Cassidulina subglobosa (H. B. Brady)
C. limbata Cushman & Hughes
Bolivina striatella Cushman
Cornuspira sp.
Cibicides gallowayi Cushman & Valentine
Trochammina pacifica Cushman
Proteonina atlantica Cushman



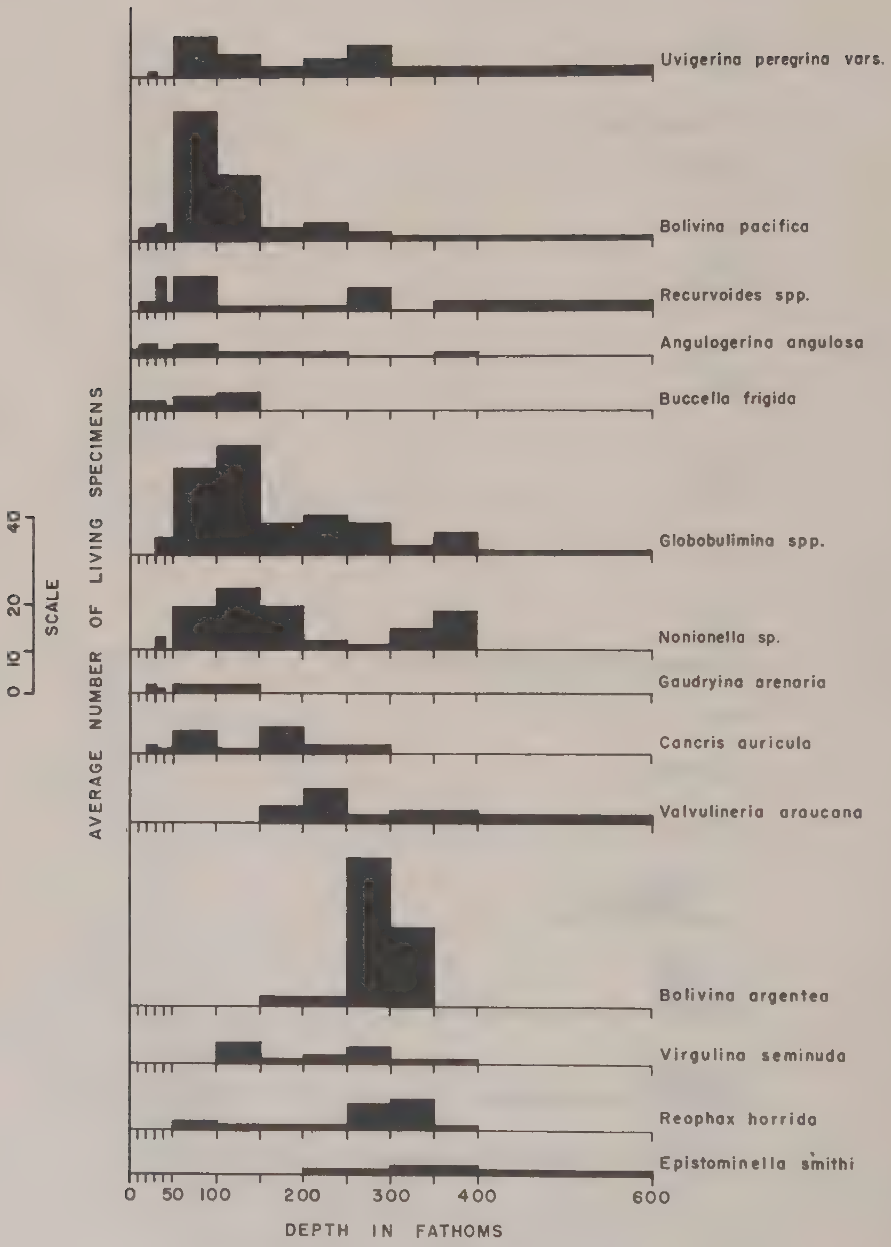
TEXT-FIG. *19*—Frequency distributions of living benthonic species.



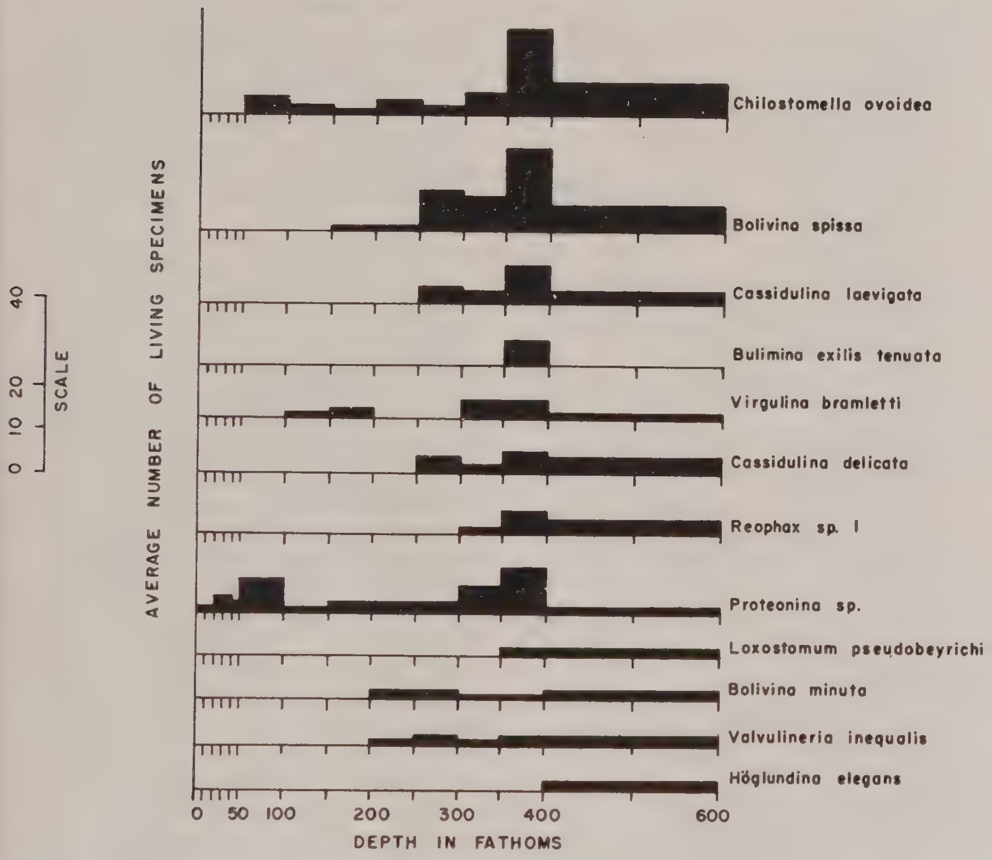
TEXT-FIG. *20*—Frequency distributions of living benthonic species.



TEXT-FIG. *21*—Frequency distributions of living benthonic species.



TEXT-FIG. 22—Frequency distributions of living benthonic species.



TEXT-FIG. 23—Frequency distributions of living benthonic species.

The second faunal boundary occurs at approximately 50 fathoms. No species are limited to 30–50 fathoms, but the following group occurs most abundantly within this range:

Nonionella miocenica stella Cushman & Moyer
Reophax scorpiurus Montfort
Robertina charlottensis (Cushman)
Textulara cf. *T. schencki* Cushman & Valentine
Nonionella basispinata (Cushman & Moyer)
Triloculina sp. 1
Cassidulina tortuosa Cushman & Hughes
Labrospira cf. *L. advena* (Cushman)
Goësella flintii Cushman
Planulina exorna Phleger & Parker
Cibicides mckannai Galloway & Wissler
Cassidulina sp.

The following species do not occur deeper than 50 fathoms:

"*Rotalia*" spp.
Reophax curtus Cushman
Triloculina sp. 1
Cassidulina tortuosa Cushman & Hughes
Labrospira cf. *L. advena* (Cushman)

The third faunal boundary occurs at approximately 100 fathoms. No species are restricted to the depth range 50 to 100 fathoms, but it is characterized by a group of species whose frequency distributions have pronounced maxima within this depth range. These species range both into shallower and deeper water, but their frequency distributions tend to be skewed more toward the deeper end of their ranges. The following species are most abundant at approximately 50–100 fathoms:

Bulimina denudata Cushman & Parker
Ammotium planissium (Cushman)
Bolivina acuminata Natland
Reophax gracilis (Kiaer)
Uvigerina peregrina Cushman vars. [part]
Bolivina pacifica Cushman & McCulloch
Recurvoides spp.
Globobulimina spp.
Nonionella sp. [part]
Angulogerina angulosa (Williamson)
Buccella frigida (Cushman)
Gaudryina arenaria Galloway & Wissler
Cancris auricula (Fichtel & Moll)

The following species do not occur deeper than 100 fathoms:

Planulina exorna Phleger & Parker
Cibicides mckannai Galloway & Wissler
Textularia cf. *T. schencki* Cushman & Valentine
Reophax scorpiurus Montfort
Bolivina striatella Cushman
Cassidulina limbata Cushman & Hughes
Eggerella advena (Cushman)

A fourth faunal boundary occurs at approximately 350–400 fathoms. The species occurring most abundantly between 100 and 350–400 fathoms are:

Valvulineria araucana (d'Orbigny)
Virgulina seminuda Natland
Reophax horrida Cushman
Bolivina argentea Cushman

Deeper than approximately 350 fathoms, a group of species appears in abundance, and these are characteristic of water greater than this depth. These are:

Chilostomella ovoidea Reuss
Bolivina spissa Cushman
B. minuta Natland
Cassidulina laevigata d'Orbigny
C. delicata Cushman
Bulimina exilis tenuata (Cushman)
Virgulina bramletti Galloway & Morrey
Reophax sp. 1
Proteonina sp. [part]
Loxostomum pseudobeyrichi (Cushman)
Valvulineria inaequalis (d'Orbigny)

Höglundina elegans (d'Orbigny) does not occur shoaler than 400 fathoms.

PLANKTONIC FORAMINIFERA

The planktonic populations were counted from three size fractions. The distribution of total populations of planktonic Foraminifera in Todos Santos Bay is shown in Text-figure 24. The largest planktonic populations correspond to the area of largest benthonic populations and, in general, with the distribution of sediment Group I. Two aspects of the distribution of planktonic Foraminifera are of interest: (1) the very large populations in certain areas of the bay, and (2) the wide distribution of planktonic species.

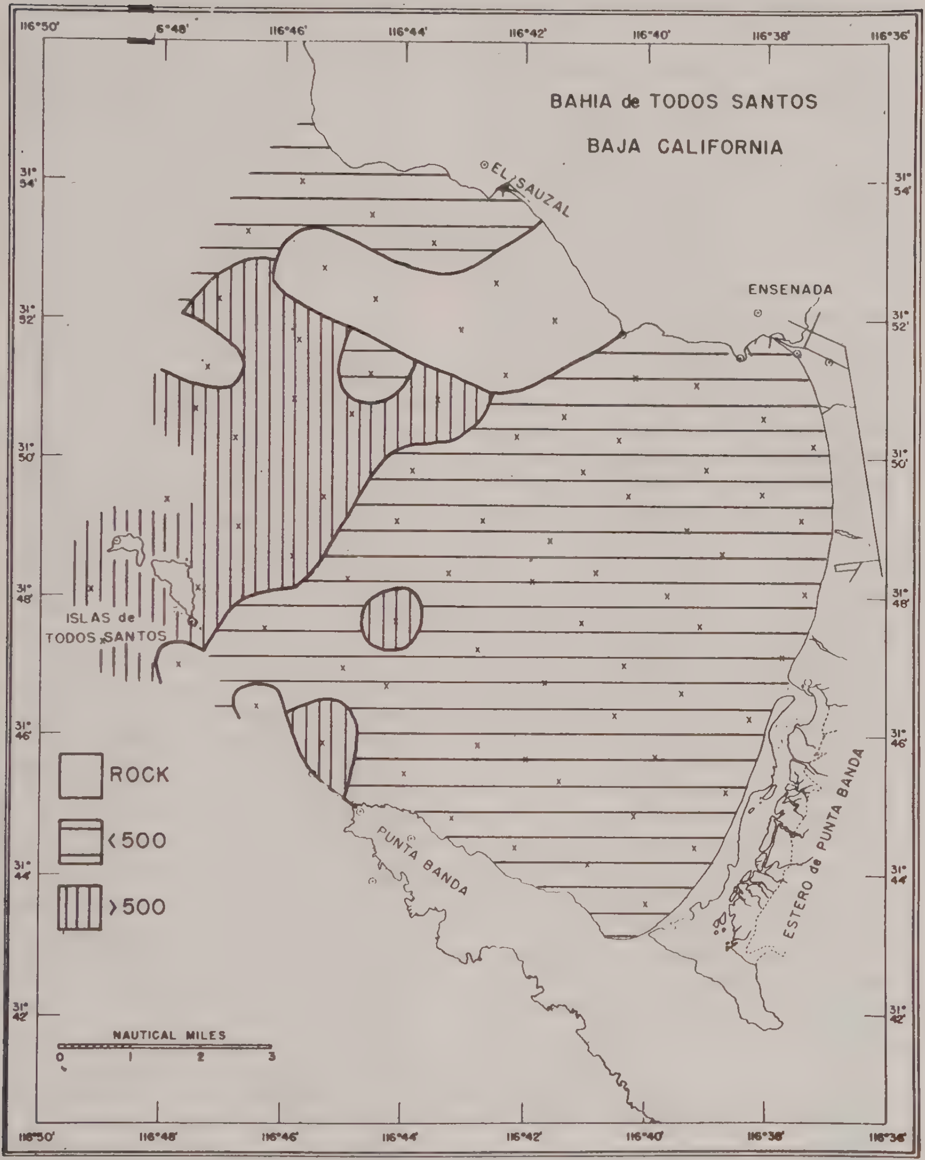
Dead planktonic Foraminifera have been found in practically all the samples examined. This wide distribution of planktonic forms and their occurrence in the Estero de Punta Banda demonstrates the apparent ease with which they are transported by currents. Phleger (1951b, p. 67) reports that planktonic Foraminifera are characteristic of offshore water masses and are seldom found in plankton tows in shoal areas. The very large planktonic populations from sediment samples in water depths less than 50 fathoms (exceeding 5,000 specimens per sample) do not appear to reflect the amount of productivity of planktonic species in the bay at the present time. Planktonic populations greater than 5,000 specimens (from comparable samples) are characteristic of water depths exceeding 1000 m. in the northwestern Gulf of Mexico (Phleger, 1951b, p. 67). These large planktonic populations appear to reflect the low rate of sedimentation in the area where they occur.

DISCUSSION OF RESULTS

COLLECTION OF SAMPLES

The stations from which sediment samples were collected in Todos Santos Bay are arranged in a one-mile grid pattern (Text-fig. 2). In the descriptions of populations from samples collected over such a grid system, the assumption is made that the population of each sample is representative of a square mile of area. The sampling error in foraminiferal studies has never been determined accurately. Phleger (1952b) and Butcher (1951) report indirect evidence from the areal distributions of species of Foraminifera that their samples were representative. Their evidence is that individual species have reasonable distributions, reach maxima, and decrease in a regular manner away from centers of greatest abundance.

The density of samples necessary to repre-


BAHIA de TODOS SANTOS
BAJA CALIFORNIA
EL SAUZAL
ENSENADA
ISLAS de TODOS SANTOS
PUNTA BANDA
ESTERO de PUNTA BANDA
ROCK
<500
>500
NAUTICAL MILES
0
1
2
3
116°50'
116°48'
116°46'
116°44'
116°42'
116°40'
116°38'
116°36'
31° 54'
31° 52'
31° 50'
31° 48'
31° 46'
31° 44'
31° 42'

TEXT-FIG. *24*—Areal distributions of planktonic Foraminifera in sediment samples in number of specimens per sample.

sent truly any variant depends upon its rate of variation. The variants measured in most foraminiferal studies are populations of the species. The rate of variation of foraminiferal populations per unit area is not the same for all species, as can be seen by a comparison of the distributions of the species in the Estero de Punta Banda with the deeper-water species in the open ocean. The rate of variation in the estero is extremely high, where populations of individual species may range from several hundred specimens to no specimens over a distance of a few feet or in some places a few inches. Large faunal variations in such environments necessitate closely-spaced samples. The open-ocean species, however, occur abundantly over depth ranges of hundreds of fathoms and distances of several miles, and samples in this environment may be spaced at greater distances and still adequately represent the populations.

The frequency distributions of living specimens of individual species in the open bay (Text-figs. 19–23) demonstrate that the populations of species occurring shallower than 50 fathoms have a higher rate of variation per unit area of sediment than do the populations deeper than 50 fathoms. This fact suggests that samples in the shoaler depths should be more closely spaced than offshore samples. In general, it appears that samples spaced closer than 1 mile apart in the bay are not necessary in order to represent accurately population variations of most foraminiferal species. The samples used in this study appear to give representative foraminiferal distributions.

It is necessary to maintain rigorous standards when collecting bottom samples for the study of living populations, and an attempt was made to eliminate as many sources of error as possible in the collection and preservation of the samples. The constant-volume sampler obtains a uniform volume of wet sediment from each sample. Immediate sampling of the cores in the field eliminated the possibility of disturbance of the samples during transit or storage.

The samples were preserved in neutral formalin at the time of collection to ensure preservation of the living Foraminifera. The use of formalin as a preservative necessitated periodic checks of the pH of the samples. Formalin decomposes with the formation of formic acid which lowers the pH of the samples. The rate at which the pH of a sample is lowered by the decomposition of formalin apparently varies with the amount of calcium carbonate in the sediment. The pH of clean, quartz sand samples, after being treated with neutralized formalin may drop below pH 7 within a few weeks. The pH of samples containing abundant remains of calcareous organisms may remain above 7 indefinitely without additional buffer.

EQUAL SAMPLES FOR COMPARATIVE PURPOSES

The problem of the type of sample from which quantitative counts of Foraminifera should be made has been given considerable attention in the literature. There appears to be two schools of thought concerning the problem of equal samples, one favoring population counts from samples of equal dry weight (Schott, 1935; Said, 1950) and the other from equal volume samples (Phleger, 1952b; Höglund, 1947; Parker, 1948; Butcher, 1951).

Most ecological work on modern Foraminifera is aimed at determining their distributions and relative abundances in modern sediments, which is a function of numerous and complex ecologic factors. Assuming that Foraminifera live at or just below the sediment-water interface, the natural measure of populations for comparative purposes should be the number of specimens per unit area. Assuming further that each environment is supporting the maximum number of Foraminifera possible, referring the population to any base other than available living space appears to be artificial. It is considered that wet volume of sediment is the only natural base to which living populations can be referred for comparative purposes.

It can be shown that the reference of benthonic foraminiferal populations to constant dry-weight samples may be misleading. The total living population at station B-111 in 6 fathoms is 75 specimens, the wet volume is approximately 10 cc., and the total dry weight is 13.8 grams. Station B-45 in 141 fathoms has a total living population of 102 specimens from a volume of 10 cc. of wet sediment, but the total dry weight of this sample is 4.28 grams. These living populations are comparable when based on equal-volume samples, but based on equal dry weights the living population at station B-45 would be approximately 4 times as great as the population from sample B-111. This fact would suggest that at depths of 141 fathoms, the environment can support 4 times as many living Foraminifera as the shallow-water environment. Such conclusions are not valid in the light of what is known about the distribution of living Foraminifera.

If the sediment samples have been washed or otherwise concentrated before the dry weight is measured, the data are even less reliable. The weights just listed for samples B-45 and B-111 include the entire sediment sample. If only the coarser fractions of the samples are considered (sizes greater than $3\frac{1}{2}\ \phi$ or 0.088 mm.), which contain most of the Foraminifera, the dry weight of sample B-45 is 1.03 grams, and that of B-111 is 7.035 grams. It is obvious that population counts from dry, previously washed, or concentrated samples are not comparable and should not be considered representative.

SIGNIFICANCE OF SIZE STUDIES

The population counts were made from three size fractions and combined to get the total populations. Text-figure 17 illustrates the populations of the size fractions for the seasonal samples, and Text-figure 18 shows the fraction populations of the size fractions for *Nonionella miocenica stella*. These figures illustrate the relatively small differences in the populations of the size fractions. Only living populations are thus illustrated but the same relationship holds for the dead populations. The only generalization that can be made concerning the populations of the size fractions is that the largest populations occur in the finer size range between 125μ and 88μ in most samples. Even this generalization is variable, however, and depends upon the size of the dominant species at the place where the sample was collected. For example, station B-348 in 8 fathoms yielded a total population of 222 living specimens. Fifty-three specimens occurred in the coarse fraction, 54 specimens in the intermediate fraction, and 116 in the fine fraction. Approximately half of the total living population consists of three small species, *Bolivina vaughani*, *Buliminella elegantissima*, and *Eggerella advena*. Station B-132 in 52 fathoms yielded a living population of 117 specimens; 68 specimens occurred in the coarse fraction, 25 in the intermediate fraction, and 24 in the fine fraction. This population consists principally of *Ammotium planissimum*, *Goësella flintii*, *Proteonina atlantica*, and *Reophax scorpiurus*, all large forms.

ESTIMATION OF TOTAL POPULATIONS

The living populations presented in Tables 1–3 are actual counts from the entire samples, and most of the dead populations are actual counts; but it was necessary to estimate large dead populations by counting a fraction of the sample. This was done by splitting the sample, using the Otto Microsplit (Otto, 1933) and no population was estimated from a fraction smaller than $\frac{1}{16}$ of the total sample.

The number of specimens to be counted in any sample depends upon the accuracy desired, and, in general, the accuracy increases as the square root of the number of specimens counted. Ovey (1950, p. 213) shows that the error diminishes as the number of specimens counted increases. His data show that there is only a small error in a species forming 70–90% of the total population where 300 specimens were counted. Butcher (1951, p. 21) points out, however, that Ovey's "estimates of error are based on only two counts of the same sample and are not statistically sound." Ovey's conclusion, that population counts of less than 300 specimens may be unreliable, however, appears to be valid.

Dryden (1931, p. 236) shows that the accuracy of mineral grain counts increases very little after 300 or 400 grains have been counted. Population counts of mineral grains or Foraminifera of less than 300 specimens show marked increases in the per cent error in species forming small percentages of the population. It is apparent that the small increase in accuracy gained by counting more than 300 or 400 specimens in any sample does not justify the time involved, but conclusions drawn from population counts of less than approximately 300 specimens may not be reliable.

Dryden (op. cit.) discusses percentage representation of heavy mineral frequencies which also are applicable to foraminiferal counts. He recommends percentage representations but objects to the presentation of percentages that indicate an unjustified degree of accuracy. More than 300 specimens have been counted from each of the present samples from which the total population was estimated. On this basis it is possible to state that the percentage occurrences greater than 5% will have a probable error not exceeding 20%. Percentage occurrences smaller than 5% probably are not so reliable but are presented as such in the tables of dead populations to allow the reader to estimate the approximate number of specimens counted. Percentage occurrences smaller than 1% are represented in Table 4 by an "X" to indicate the occurrence of these species.

ECOLOGIC SIGNIFICANCE OF THE ESTERO FAUNAS

The marginal environment characteristic of the Estero de Punta Banda probably represents the most rigorous type of marine environment in which benthonic Foraminifera can flourish. Temperature and salinity measurements made in November, 1951, over a span of two days show large variations. Annual variations in the same area are more extreme according to Carl L. Hubbs (personal communication). In such an environment, marked variations in foraminiferal populations would be expected and have been reported from several marsh areas (Phleger and Walton, 1950; Parker, Phleger, & Peirson, 1953; Phleger, 1954).

There are three striking features of the Estero de Punta Banda fauna: (1) the discrete ranges of the species, (2) the occurrence of relatively few species, and (3) the predominantly arenaceous character of the fauna.

The discrete distributions of the marsh faunas appear to be related to the sharp variations in distribution of the marsh flora. Different foraminiferal assemblages seem to occur in areas characterized by marsh grasses and in general coincide with their distributions. Areas of marsh grasses support abundant populations of a great variety of invertebrates, and the air-water substrata boundary is generally covered by a thin layer of algae. The Foraminifera probably live in close contact with the continuously wetted surface of the grasses.

It is interesting that very few living specimens of the marsh species are found in the open ocean. If temperature and/or salinity alone controlled the distributions of these species they would be expected to occur in abundance in the open ocean where temperatures and salinities are within the range of those obtaining the marsh. Their distributions probably result from other ecologic factors, such as food association, etc., which limit these species to areas containing marsh grasses.

The occurrence of relatively few species in the marsh faunas may be due to the extreme variations of temperature and salinity in this environment. A variable environment generally would be expected to support a greater number of species than an environment characterized by small ranges in temperature and salinity, provided the variations are not extreme. Assuming abundant food and living space, the environmental variations of the marsh should include the optimum temperature and salinity for a large number of species. The extreme variations of temperature and salinity in the marsh apparently exceed the viable or reproduction limits of many species. There appear to be relatively few species whose tolerances fall within the limits of the ecologic variations found in the marsh environments.

The dominantly arenaceous character of the marsh fauna may be related to a deficiency in the calcium carbonate content of the marsh water. Two calcareous species were found living in the marsh area of the Estero de Punta Banda, *Elphidium* sp. and *Triloculina* sp. 2. "*Rotalia*" *beccarii* variants are abundant in the marshes of San Antonio Bay Texas (Parker, Phleger, & Peirson, 1953). The latter example may be due to storm overwash from the lagoon where abundant populations of "*Rotalia*" *beccarii* also are found.

Three species are found living in both the tidal channels and marshes. These species are able to withstand the extremes of the marshes but do not appear to be as restricted in their environmental associations as do the marsh species. These are *Miliammina fusca*, *Proteonina* sp., and *Elphidium tumidum*. *Triloculina* sp. 2 and "*Rotalia*" *beccarii* are restricted to the tidal channels. The species in the tidal channels that are common in the bay indicate that certain open-ocean forms are able to survive in the channels. They further suggest that the channel environment is not so rigorous as the intertidal marsh environment, and that the conditions in the channel closely approximate those in the bay.

LIVING FORAMINIFERAL FAUNAS IN THE BAY

It is known that some Foraminifera have tolerances of temperature outside of which they cannot reproduce (Myers, 1936, p. 121). As with other groups of animals, it appears that these temperature tolerances are not the same for every species of Foraminifera. Phleger (1951b, 1952a, 1952b), Parker (1948, 1952a), and Natland (1933) have reported depth facies of Foraminifera which may be related to temperature changes, at least in part.

The areal distributions of the outer bay facies and the middle bay facies in Todos Santos Bay appear to be related to the bathymetry, and probably also to the associated temperature variations. It is interesting that all the species of the middle bay facies are arenaceous, imperforate forms. It is possible that some peculiarity of food requirements, feeding habits, or other ecological factors may influence these distributions.

The species of the marginal bay facies have wider distributions than the outer or middle bay facies, and generally are distributed over the area of coarser sediments (Text-fig. 6). The fact that this assemblage is most commonly associated with coarser sediments suggests that sediment type may exert some influence on the distributions of these species. This correlation may be fortuitous, however, and the distribution of this facies may be more closely related to the food requirements or to some other ecologic factor. This area of coarser sediments appears to have a pronounced effect on the benthonic organisms other than Foraminifera. Two species of brachiopods, several echinoids, and abundant encrusting organisms were collected in dredge samples from this area yet were not found elsewhere in the bay. Three species of Foraminifera, *Cibicides fletcheri*, *Cibicidina nitidula*, and *Planulina exorna*, were found living free and also attached to the larger sediment particles and shell fragments. It appears that sediment type may influence some distributions in this group either directly, or indirectly through food associations.

Geographic facies have been presented in addition to depth distributions for the primary purpose of delineating foraminiferal assemblages that may be related to ecological factors other than temperature. The geographic facies apparently indicate that areal distributions of species and groups of species may be influenced by sediment type, food associations, or other ecologic factors. These associations are not apparent from depth distributions which probably are more related to temperature variations.

DEPTH DISTRIBUTIONS OF LIVING FORAMINIFERA

In addition to faunal boundaries at 30 fathoms, 50 fathoms, 100 fathoms, and 350 fathoms, two general characteristics of the distributions of living Foraminifera stand out: (1) the relatively greater number of species in the shoaler depths, and (2) the wider distributions of the deep species. It can be seen from Text-figures 19–23 that the greatest number of species is restricted to or occur most abundantly at depths shoaler than 50 fathoms. Over 50% of the species are most abundant shoaler than 50 fathoms, and 67% are most abundant shoaler than 100 fathoms. This distribution suggests that the variable environment of the shoaler depths supports a greater variety of benthonic Foraminifera. The effect of the variable environmental conditions on the size of living populations is indicated by the productivity estimates presented on following pages. They suggest that depths between 20 and 50 fathoms are approximately 6 times as productive as the zone between 350 and 400 fathoms.

The variable environmental conditions characteristic of the shoaler depths apparently have a marked limiting effect on the distributions of the foraminiferal species. Most of the species characterizing the 0–30 and 30–50 fathoms facies are distributed over relatively narrow depth ranges; they seldom occur over depth ranges greater than 100 fathoms (Text-figs. 19, 20, 21). The species characterizing facies deeper than 50 fathoms commonly range over hundreds of fathoms. This wider distribution of deeper-water species is apparently characteristic of distributions of benthonic organisms in the archi-benthic and abyssal-benthic environments (Ekman, 1953, p. 286). These wider distributions apparently reflect the more uniform environments characterizing the deeper water.

SEASONAL VARIATION OF LIVING POPULATION

As previously noted, individual species do not all have their maximum abundances during the same season. The seasonal peaks reflect relative abundances of different groups of species, one group occurring most abundantly in June and the other in August. Of the two peaks, however, August marks the season of greatest abundance of benthonic Foraminifera in this area. The temperature maximum in August suggests that warmer water may favor large populations of benthonic Foraminifera in the presence of abundant food.

It is believed that the population maxima in June and August reflect peaks of phytoplankton production in late spring and again in summer. Very little information is available on the food of Foraminifera. Glaessner (1947, p. 57) reports that they eat "diatoms and other algae, either alive or in a state of decay . . . copepod crustaceans . . . copepod larvae and infusoria as well as diatoms." Phleger (MS.) reports that they feed on any form of organic detritus. From these data, the foraminiferal populations would be expected to respond to the abundance of phytoplankton during the late spring and the summer months.

Myers (1942b) in his work on *Elphidium crispum* off Plymouth, England, reports that the growth and reproduction of Foraminifera are similar to those of the zooplankton, both of which respond to the abundance of food available in the microflora of the sea. He states further (op. cit., p. 334) that the season of maximum growth and reproduction of *Elphidium crispum* follows closely behind the spring flowering of the phytoplankton off Plymouth. The work of Myers has been a major source of information on the life cycle, food, habits, and reproduction of Foraminifera in the sea, but the variability of distribution and morphology between species probably precludes application of his specific data to all species.

The large variations in nearshore surface temperatures on the south side of Punta Banda, due to upwelling, apparently do not affect the composition of the foraminiferal fauna in this area. The populations of the samples collected in areas of upwelling are comparable to the populations from similar depths in the bay in both kind and number. Temperature measurements indicate that bottom temperatures at a depth of 50 fathoms in the area of upwelling are only a few degrees colder during times of upwelling than sediment temperatures at comparable depths in the bay. It is possible that the nearshore, shallow-water faunas would be affected by the relatively larger surface temperature variations.

The cold, upwelled water on the south side of Punta Banda during the late spring and summer months apparently is confined outside of Todos Santos Bay and has no noticeable effect on water temperatures in the bay. Temperature data in June suggest that the upwelled water extends northward toward the Todos Santos Islands but apparently is confined outside the bay by the outflowing bay water.

RATES OF PRODUCTION

The apparent rate of production of benthonic Foraminifera varies with depth and no generalization can be made concerning the rate of production for the entire area. Depth distributions of average living populations for all seasons (Text-fig. 16) show that there is an average of 104 living specimens per sample at depths shoaler than 50 fathoms. From 50 to 100 fathoms the living populations average 142 specimens per sample, and from 100 fathoms to the end of the seasonal traverse at approximately 600 fathoms, the average is 42 specimens. These data suggest that the zone of maximum production of benthonic Foraminifera in this area is at 50–100 fathoms.

Text-figure 16 is a scale agreement histogram in which the depth shoaler than 50 fathoms is divided into 10-fathom intervals. This shows a prominent peak at 30–40 fathoms which is the actual depth of maximum production. This histogram includes all the stations from which living counts were made, and the large number of nearshore, low population stations from the February sampling lower the averages of the populations shoaler than 50 fathoms. The histogram of the seasonal traverses (Text-fig. 15) verifies the 30–40 fathom production maximum. Considering only those seasonal samples that were collected within the depth range of 20–50 fathoms, the average living population per sample is 193 specimens; the minimum value occurs during March with 25 specimens per sample, and the maximum population occurs during August, with 653 specimens per sample.

Myers (1942b, p. 336) found that populations of *Elphidium crispum* in Plymouth Sound varied from 245 individuals per square foot in February to 1,225 individuals per square foot in June. He concluded that since the life span of *E. crispum* in tidepools is one year, the annual rate of mortality is equal to the total number of individuals produced each year. He also concludes (op. cit., p. 338):

> "In the sublittoral zone the number of tests annually contributed to the sediments also approximates the maximum population observed including those which had survived from the preceding year."

If we assume that the life cycle of benthonic Foraminifera is one year, approximately 650 specimens per year per 10 cc. or 650,000 specimens per sq. m. are added to the sediment at 20–50 fathoms. The seasonal samples collected at 300–400 fathoms have an average population of 50 specimens per sample. The maximum number of specimens within this depth range occur in March with an average of 104 specimens per sample, and the minimum during November with an average of 25 specimens per sample. Assuming one year as the life cycle of benthonic Foraminifera, approximately 100 specimens per year per 10 cc. or 100,000 specimens per sq. m. are added to the sediment within this depth range. These data are very general and are given only as representing orders of magnitude. The assumption of one year for the life cycle of benthonic Foraminifera in the 20–50 fathom range may be valid, but in the deeper range (300–400 fathoms) the life cycle may be longer due to the much colder temperatures.

The average standing crop of living Foraminifera in Todos Santos Bay is approximately 193,000 specimens/sq. m. from 20 to 50 fathoms. Phleger (1951b, 1952b) made similar calculations on the continental shelf in the Gulf of Maine and the Gulf of Mexico. He found an approximate standing crop of 30,000 specimens/sq. m. in the Gulf of Maine and 10,000 specimens/sq. m. in the northwest Gulf of Mexico. These estimates were made from comparable samples and are from comparable depths. The reasons for these discrepancies in average standing crops of living Foraminifera are not apparent to the writer, but it is possible that Phleger's season of collection has some effect. The estimate of 193,000 specimens/sq. m. is a yearly average in contrast to the estimates from the Gulf of Maine and the Gulf of Mexico which are average populations at one season. It is suggested that the lower estimates may reflect seasons of lower production in the other areas. It also is suggested that Phleger's lower estimates may be due to the different methods used to recognize the living specimens; Millon's reagent in the Gulf of Maine, biuret reaction in the Gulf of Mexico, and rose bengal staining technique in the present study. Recent work in the Gulf of Mexico near the Mississippi Delta shows an average standing crop of 90,000 specimens/sq. m. using the rose bengal technique (Phleger, unpublished data). This estimate also was made at only one season but more closely approximates the yearly average of 193,000 specimens/sq. m. of this study.

NON-LIVING DISTRIBUTIONS

There are two striking differences in the distributions of living and dead specimens of the species found in this area: (1) differences in areal distribution, and (2) differences in size of populations. Differences in areal distributions of living and dead specimens of various species in this area are of considerable importance. Most ecological and faunal studies of benthonic Foraminifera have been made from dried samples and it has been assumed that dead populations in general represent distributions of the living Foraminifera. Phleger (1951b, 1952b) has shown that this assumption is generally correct by considering the living populations as well as the dead. The results of the present study have shown that this assumption is valid only under certain conditions. The areas of largest populations of empty shells do not necessarily coincide with the areas of maximum abundances of living Foraminifera. This fact is due primarily to varying rates of sedimentation. In areas of little or no sedimentation, large populations of empty shells accumulate. Areas undergoing rapid sedimentation, on the other hand, might have a relatively small population of empty shells even though both areas have comparable living populations.

Areal plots of living and dead distributions in the present area suggest that dead populations generally occur over a somewhat wider areal and depth range than do the living populations. It is believed that dead population counts are valid in describing the composition and general distributions of living benthonic Foraminifera, unless contaminated with relict or fossil faunas, but cannot be considered as indicative of relative abundance.

SIGNIFICANCE OF POPULATION RATIOS

The L/D ratio is an index of the complex variables which control the living and dead populations at any location. The size of the living population results from the ability of the organisms to live and reproduce in the environment. It may be assumed that any given environment is supporting the maximum possible population of Foraminifera, and that the population will increase or decrease in response to changes in food supply, biologic competition, predators, or changes in the environment. The total living populations in the immediate area of Todos Santos Bay vary over a relatively small range. Even though the populations and distributions of individual species vary considerably, the small variation in the total living populations suggests that the bay environment can support relatively uniform numbers of living Foraminifera over most of its area. There is no indication that large variations in the productivity from place to place in the bay are responsible for the large variations in populations of empty tests.

The adaptability of the empty tests to preservation in the sediments is an important factor in the accumulation of large dead populations. In the depth ranges considered in this report there is no indication that appreciable destruction of empty tests occurs, below the depth of vigorous abrasion (*i.e.*. the surf zone). Certain very fragile arenaceous forms rarely are found dead, such as *Reophax* sp. 1 and *R. gracilis*, but these constitute relatively small percentages of the total populations.

It appears that dilution by detrital sediment is the most important factor in determining the total dead population per unit volume of sediment. The L/D ratio appears to be a good index to relative rates of sedimentation in this area, since the total living populations vary little over the area of the bay. Where the L/D ratios are large, more detrital sediments are being deposited to dilute the dead populations than in areas where the L/D ratio is small. The areas of low L/D ratios in Todos Santos Bay correspond generally with the areas of sediment Group I. The sediment data indicate that little sediment is being deposited in the Group I area at the present time, and further that the sediments of Group I are not characteristic of the environment in which they are found but are "relict" sediments of a previous environment. The foraminiferal faunas of the area corresponding with Group I sediments also appear to be relict, at least in part. Several species were found in this area for which there were no living representatives. Occasional specimens of *Elphidium crispum* and the large populations of miliolids indicate an environment shoaler than the present depths. The portion of the dead populations in the relict area which represents a previous environment is not known since most species were representated by living forms. The relatively low rates of sedimentation in the relict area appear to be the primary factor causing the unusually large populations of dead Foraminifera. These large dead populations do not indicate high productivity, therefore, but do indicate low rates of sedimentation.

FOSSIL FAUNAS

Dead populations were counted from only one seasonal traverse. The dead populations of the samples in deeper water are relatively large and contained several species which are not represented by living specimens. The species which are not found living are:

Angulogerina carinata Cushman
Astrononion stellatum Cushman & Edwards
Bulimina pagoda Cushman
B. subacuminata Cushman & Edwards
Cassidulina californica Cushman & Hughes
Eponides subtenera (Galloway & Wissler)
E. umbonatus (Reuss)
Gyroidina altiformis Stewart & Stewart
Planulina ariminensis d'Orbigny
Sigmoilina cf. *S. miocenica* Cushman
Uvigerina senticosa Cushman

These species are abundant in the surface sediment samples at most of the deeper stations.

At stations B-141, B-160, and B-144, the small coring tube penetrated the fine surface sediment and cored hard dark siltstone. These siltstones were found to contain abundant fossil Foraminifera. The age of these fossil assemblages was identified for the writer by Mr. Thomas Rothwell of the Richfield Oil Company.

Sample B-141 at a depth of 440 fathoms contains a fauna referred to the Venturian stage of the Pliocene (lower Pico). Sample B-160 at a depth of 265 fathoms contained a fauna identified as of middle Pico age (Wheelerian stage of Natland). Sample B-144 at a depth of 380 fathoms contained a fauna which was identified as characteristic of the upper Luisian stage of the Miocene. These fossil faunas all occurred only a few inches below the surface of the core. All of the species just listed, for which no living representatives were found, occur abundantly throughout the Pliocene and in the siltstones cored at stations B-141 and B-160. The presence of these non-living species in the Recent sediments and their abundances in the Tertiary rocks outcropping nearby suggest that they do not live on the continental shelf off Baja California, but are contaminants from the submarine reworking of the Tertiary rocks.

It is realized that the area sampled is small and the samples are few and that no generalization can be made concerning the effects of reworked Foraminifera in other areas. It also is realized that these species may occur living in deeper facies or may be so sparse that they were not found in the small area sampled by the cores. It appears certain, however, that these Tertiary rocks and their contained faunas outcropping at or near the surface of the continental shelf contaminate the Recent sediments.

SUMMARY OF CONCLUSIONS

1. The sediments of Todos Santos Bay can be divided into three groups on the basis of their median diameter, standard deviation, and skewness. Sediment Group II is composed of clean fine sand and covers most of the inner part of the bay. Sediment Group III is composed of micaceous silts and appears to be the seaward extension of Group II sediments. It is believed that these groups reflect the present environment of deposition. Sediment Group I is composed of coarse sand, encrusted cobbles and pebbles, abundant glauconite, and organic remains and does not appear to be in adjustment with the present environment. The sediment characteristics of this group, their geographic and bathymetric position, and the relationship with the other sediment groups suggest that they are relict and/or residual sediment of a previous environment.

2. The benthonic Foraminifera in Todos Santos Bay can be grouped into four areal assemblages. The outer bay and middle bay foraminiferal facies have limited distributions and are restricted to the deeper portion of the bay. These distributions apparently are related to depth changes and associated temperature variations. The marginal bay assemblage has a wider distribution and generally is found over the areas of coarser sediment. This assemblage does not appear to be restricted by depth or temperature variations, and it is suggested that these distributions may be related to variations in sediment type, abundance of food or other ecological factors. The species of the inner bay assemblage are most abundant in the shallow, nearshore area of the inner bay, but generally are distributed over the entire Todos Santos Bay. Their distributions do not appear to be as limited by depth changes or variations in sediment as do the species of other assemblages. These species probably have a greater tolerance for environmental changes than the previous groups.

3. Four depth facies have been established based on frequency distributions of individual species; less than 30 fathoms, 30–

50 fathoms, 50–100 fathoms, and deeper than 350–400 fathoms.

4. The areas of maximum populations of living Foraminifera do not coincide with the areas of maximum dead populations. The living specimens of a species generally are more restricted in their distributions than the dead specimens. Population counts of dead Foraminifera may be reliable only to define faunal compositions and general distributions of species.

5. Ratios of living and dead populations from sediment samples appear to be good indices of relative rates of sedimentation. Areas of low living-dead ratios suggest slow deposition and areas of high living-dead ratios suggest relatively faster deposition.

6. The production of benthonic Foraminifera varies seasonally in Todos Santos Bay and the maximum abundances occur in June and August. Each species apparently does not have its maximum abundance during the same season.

7. The population maxima in June and August apparently are related to the late spring and late summer flowering of phytoplankton in the area. The seasonal temperature maximum which occurs in August may influence the greater production during that month.

8. Many species of Foraminifera occurring in surface sediments have not been found living in the area. The occurrence of non-living, shallow-water species in the area of relict sediments suggest that part of the foraminiferal fauna may be relict and reflect a previous environment.

9. Two exposures of Middle Pliocene strata and one of Middle Miocene strata have been cored in place off Todos Santos Bay. The common occurrence of several non-living species in the surface sediments over or near these outcrops of older Tertiary sediments suggests that they may be contaminants and not representative of living populations. The occurrence of relict and/or fossil Foraminifera in modern sediments may be an important factor in interpreting distributions of modern Foraminifera.

THE BENTHONIC FORAMINIFERAL SPECIES AND THEIR DISTRIBUTION

The following is a brief discussion of the species of benthonic Foraminifera that were identified and used in this study. No attempt has been made to include detailed taxonomic discussion or complete synonomy of the species listed here. The synonomy includes only references to original descriptions of the species, and taxonomic discussion is limited to those species about which there is some question. A brief discussion of the distribution of living and dead specimens in the area of Todos Santos Bay is included for each species. The species are listed here in alphabetical order. The plates are arranged systematically.

AMMODISCUS PACIFICUS Cushman & Valentine

Plate 99, figure 11

Ammodiscus pacificus CUSHMAN & VALENTINE, Contrib. Dept. Geol. Stanford Univ., vol. 1, no. 1, p. 7, pl. 1, fig. 1.

The limited occurrence of this species of Foraminifera on the south side of Punta Banda in about 55 fathoms suggests that its distribution is controlled in the main by the colder water in this area. This area is characterized, during certain months, by upwelling.

AMMOTIUM PLANISSIMUM (Cushman)

Plate 99, figures 20–23

Haplophragmoides planissima CUSHMAN, 1927, Bull. Scripps Inst. Oceanog., Tech. ser., vol. 1, no. 10, p. 135, pl. 1, fig. 6.

This species is placed in the genus *Ammotium* (Loeblich & Tappan, 1953) because it tends to uncoil in the last chambers and the aperture becomes terminal. It differs from the genus *Ammobaculites* in that the last-formed chambers tend to uncoil but reach back to the coil at the inner margin. The specimens range from coarsely arenaceous forms, in the shallower end of their distribution (Pl. 99, figs. 20, 21) to almost entirely chitinous forms covered with a thin layer of fine silt or clay-size sediment particles at greater depths (Pl. 99, figs. 22, 23).

The depth range of the living specimens of this species is from 8 to 380 fms. Its distribution shows a marked peak between 50 and 100 fms. (Text-fig. 21). The geographic distribution in Todos Santos Bay is restricted to the area of finer sediments in and around the deeper portion.

ANGULOGERINA ANGULOSA (Williamson)

Uvigerina angulosa WILLIAMSON, 1858, Rec. Foram. Gt. Britain, p. 67, pl. 5, fig. 140.

This form is quite variable and generally smaller than the type specimens but appears to be the same species.

The depth range of this species is from 3 to 360 fathoms in Todos Santos Bay. It is most abundant between 20 and 100 fathoms. It has a wide geographic range with the greatest abundance in the area of relict sediments.

ANGULOGERINA CARINATA Cushman

Plate 102, figure 21

Angulogerina carinata CUSHMAN, 1927, Bull. Scripps Inst. Oceanog., Tech. ser., vol. 1, no. no. 10, p. 159, pl. 4, fig. 3.

This species was not found living in the area studied. The only recorded occurrences are at stations B-135, 136, 138, 141, and 141–1. All of these stations occur over or near outcrops of "fossil" sediments, and the specimens found are believed to be reworked from these older sediments.

ARENOPARRELLA MEXICANA (Kornfeld)

Plate 101, figures 1–3

Trochammina inflata (Montagu) var. *mexicana* KORNFELD, 1931, Contr. Stanford Dept. Geol., vol. 1, p. 86, pl. 13, figs. 5a–c.

Arenoparrella mexicana KORNFELD, 1951, Contr. Cushman Found. Foram. Res., vol. 2, pt. 3, p. 96, pl. 11, figs. 4 a–c.

There is no other known occurrence of this species on the west coast of North America, but it is common in the shallow nearshore areas and marshes of the Gulf Coast of Louisiana, Mississippi, Alabama, and Texas.

Living representatives of this species only occur in the marsh areas of the Estero de Punta Banda and are slightly smaller than the Gulf Coast individuals. Dead specimens are common in the marsh areas and the channel stations.

ASTRONONION STELLATUM Cushman & Edwards

Plate 101, figure 21

Astrononion stellatum CUSHMAN & EDWARDS, 1937, Contr. Cushman Lab. Form. Res., vol. 13, p. 32, pl. 3, figs. 9–11.

No living representatives of this species were found in the samples studied. Only one specimen was found in the bay. The other occurrences were at stations B-137, 138, 139, and 140. The specimens recorded from these stations are apparently mixed with reworked material and may represent an ancient environment.

BIFARINA HANCOCKI Cushman & McCulloch

Plate 101, figure 22

Bifarina hancocki CUSHMAN & MCCULLOCH, 1942 Allan Hancock Pacific Exped., vol. 6, no. 4, p. 225, pl. 28, figs. 13–19.

This species has a spotty distribution in Todos Santos Bay in depths of 6 to 27 fathoms. It occurs in the greatest abundance at station B-66 in 27 fathoms.

BOLIVINA ACUMINATA Natland

Plate 102, figure 5

Bolivina acuminata NATLAND, 1946, in CUSHMAN & GRAY, Cushman Lab. Foram. Res., Spec. Publ. 19, p. 34, pl. 24, fig. 46.

Bolivina subadvena Cushman var. *serrata* NATLAND, 1938, Bull. Scripps Inst. Oceanog. Tech. ser., vol. 4, p. 145, pl. 5, figs. 8, 9.

The living-distribution curve of this species shows a maximum abundance between 50 and 100 fathoms (Text-fig. 21) in Todos Santos Bay. The total depth range is from 3 250 fathoms. It has a restricted geographic distribution and occurs most commonly in the deeper portions of the bay. It is one of the more common species in the depth range just mentioned.

BOLIVINA ARGENTEA Cushman

Plate 101, figures 26, 27

Bolivina argentea CUSHMAN, 1926, Contr. Cushman Lab. Foram. Res., vol. 2, pt. 2, p. 42, pl. 6, fig. 5.

The only occurrences of this species in Todos Santos Bay are confined to the deeper portions. The living specimens show a fairly restricted depth range, from 150 to 350 fathoms. Its frequency distribution has a marked peak at 250–300 fathoms (Text-fig. 22).

BOLIVINA MINUTA Natland

Plate 102, figure 2

Bolivina minuta NATLAND, 1938, Bull. Scripps Inst. Oceanog., Tech. ser., vol. 4, no. 5, p. 146, pl. 5, fig. 10.

This species shows a constant living distribution below 200 fathoms. No marked peak occurs in its frequency distribution (Text-fig. 23), but it appears to be a good indicator of water depths greater than 200 fathoms off Mexico.

BOLIVINA PACIFICA Cushman & McCulloch

Plate 102, figure 4

Bolivina acerosa Cushman var. *pacifica* CUSHMAN & MCCULLOCH, 1942, Allan Hancock Pacific Exp., vol. 6, no. 4, p. 185, pl. 21, figs. 2, 3.

The living depth range of this species in Todos Santos Bay is from 18 to 490 fathoms, and its frequency curve shows an excellent distribution with the peak at 50 to 100 fathoms. It is restricted to the deeper portions of the bay between Punta Banda and the Todos Santos Islands.

BOLIVINA cf. B. PSEUDOPLICATA Heron-Allen & Earland

Plate 102, figure 1

Bolivina pseudoplicata HERON-ALLEN & EARLAND 1930, Jour. Roy. Micr. Soc., ser. 3, vol. 50, p. 81, pl. 3, figs. 36–40.

This form, which is the same assigned to *B. pseudoplicata* by Cushman and McCulloch (1942), has a widespread occurrence along the eastern Pacific coast.

No living representatives of the species were found in this study. The distribution in Todos Santos Bay is "spotty," and only a few specimens were found.

BOLIVINA SEMINUDA Cushman

Bolivina seminuda CUSHMAN, 1911, U. S. Nat. Mus., Bull. 71, pt. 2, p. 34, text fig. 55.

No living specimens of the species were found in this study. It occurs at only two stations in Todos Santos Bay but is present in sample B-141-1 which contains a pure Pliocene assemblage. It is believed that this species, where it occurs in Recent sediments, represents reworking of a fossil fauna.

BOLIVINA SPISSA Cushman

Plate 101, figures 24, 25

Bolivina subadvena Cushman var. *spissa* CUSHMAN, 1926, Contr. Cushman Lab. Foram. Res., vol. 2, pt. 2, p. 45, pl. 6, figs. 8a–b.

This species is characteristic of water depths greater than 189 fathoms off Todos Santos Bay. The frequency distribution of the living specimens (Text-fig. 23) shows a marked maximum between 350 and 400 fathoms, and it generally occurs in relatively high frequencies within this range.

BOLIVINA STRIATELLA Cushman

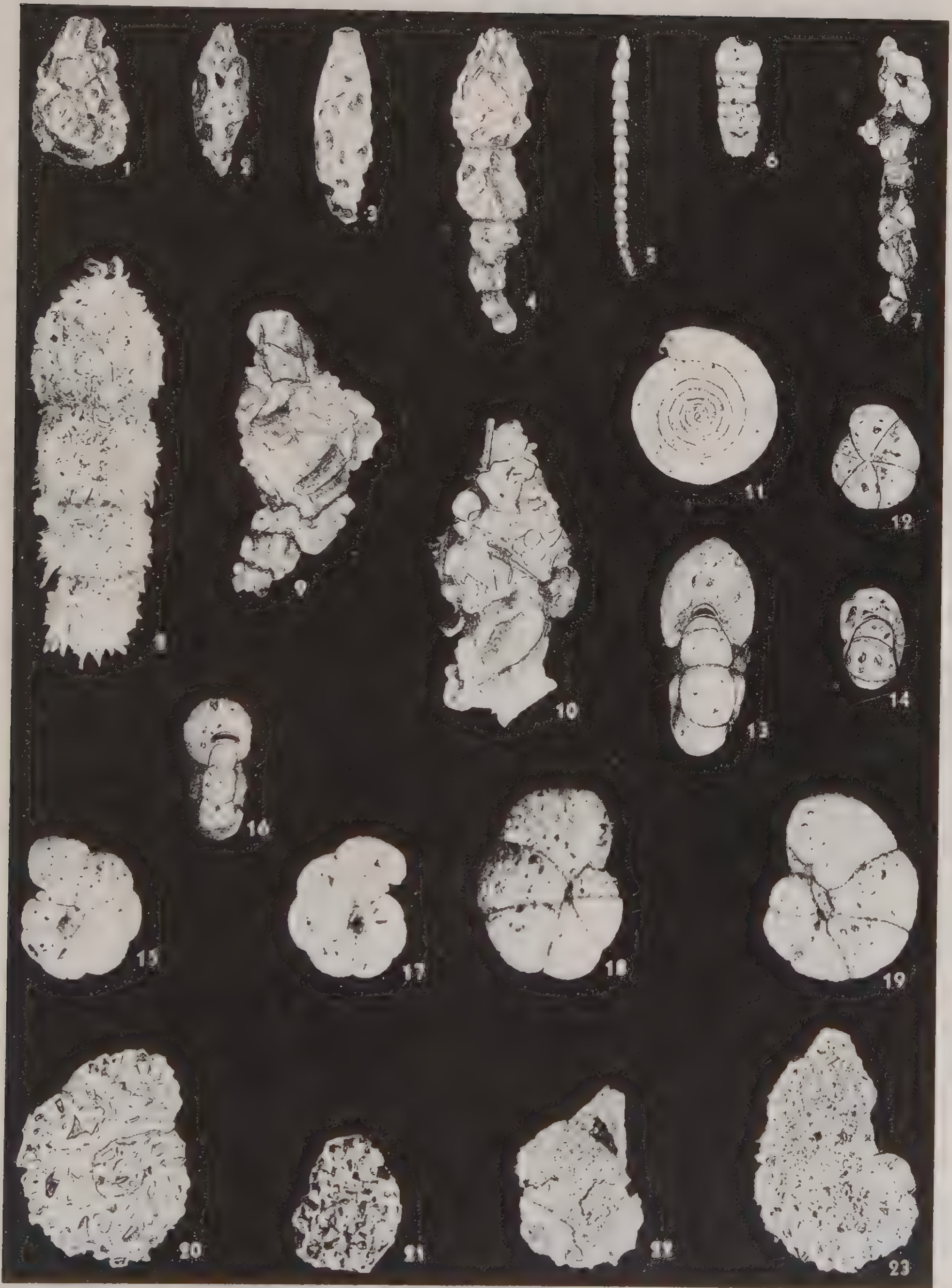
Plate 102, figure 3

Bolivina advena Cushman var. *striatella* CUSHMAN, 1925, Contr. Cushman Lab. Foram. Res., vol. 1, pt. 2, p. 30, pl. 5, figs. 3a–b.

This species was described from the Monterey shale (Miocene) of California and has also been reported from the Pliocene of California. It has been reported in Recent sediments from off California in 14 to 123 fms. Bandy (1953) has included this species under a new variety, *B. advena* Cushman var. *actula* Bandy on the basis of the arcuate rather than sinuate sutures. The specimens from Todos Santos Bay are variable, and even though some have arcuate sutures in the early chambers, the sutures of the later-formed chambers are sinuate and the writer feels that a new variety is not warranted.

EXPLANATION OF PLATE 99

FIG. *1*—*Proteonina atlantica* Cushman. ×46.
2, 3—*Proteonina* sp. (2) ×46; (3) ×70.
4—*Reophax scorpiurus* Montfort. ×30.
5—*Reophax gracilis* (Kiaer). ×30.
6—*Reophax* sp. 2. ×70.
7—*Reophax* sp. 1. ×46.
8—*Reophax horrida* Cushman. ×21.
9—*Reophax curtus* Cushman. ×30.
10—*Reophax agglutinatus* Cushman. ×33.
11—*Ammodiscus pacificus* Cushman & Valentine. ×26.
12, 14—*Recurvoides* spp. ×94.
13, 18, 19—*Labrospira* cf. *L. columbiensis* (Cushman). ×46.
15–17—*Labrospira* cf. *L. advena* (Cushman). ×46.
20–23—*Ammotium planissimum* (Cushman). ×21.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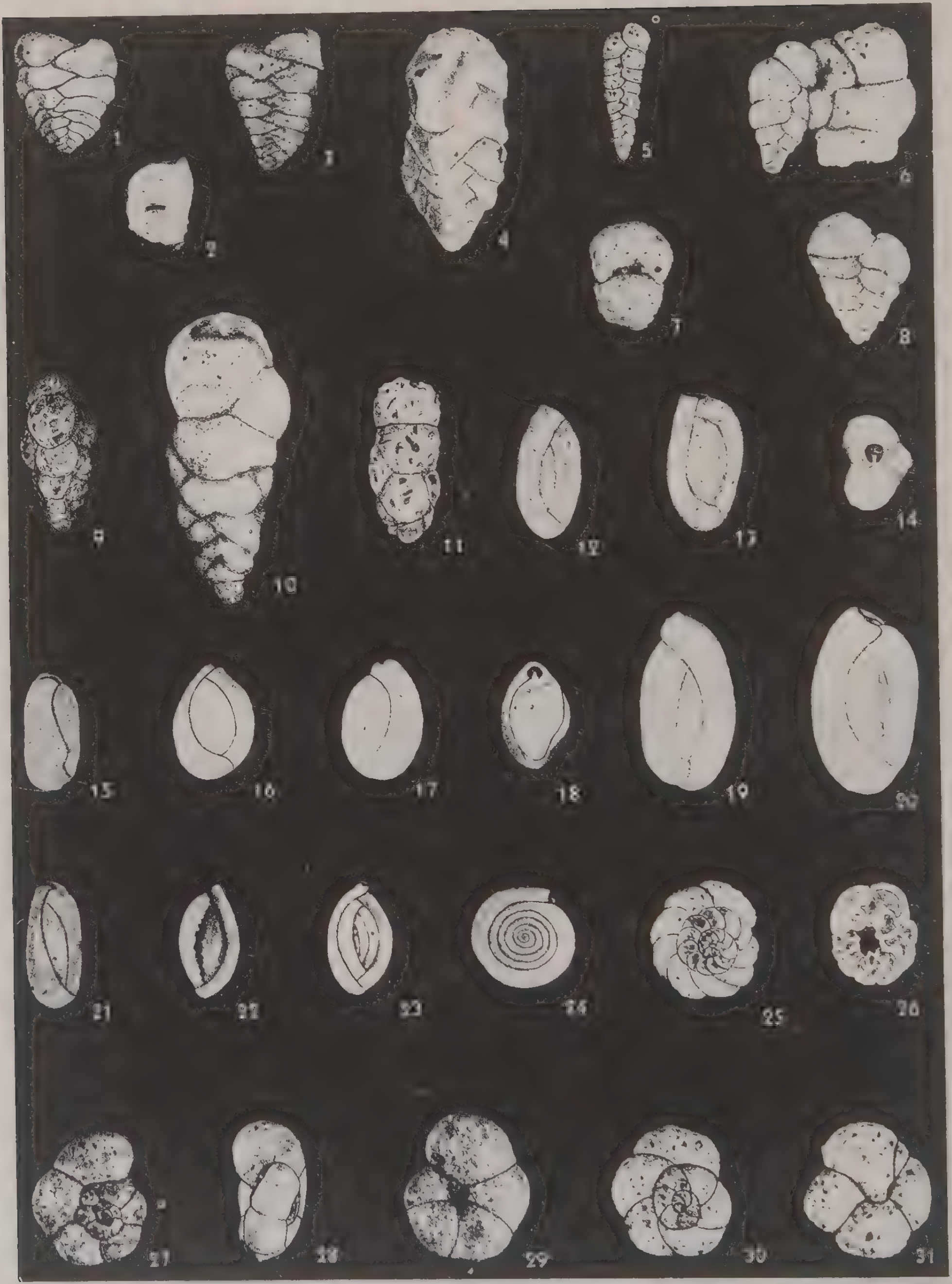
Walton, Living Foraminifera from Baja California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Walton, Living Foraminifera from Baja California

Bandy records the species from 200 to 800 ft. off San Diego.

Living specimens of this species are apparently restricted to depths shallower than 96 fathoms in Todos Santos Bay. Its frequency distribution shows a peaked tendency between 20 and 30 fathoms.

BOLIVINA VAUGHANI Natland
Plate 101, figure 23

Bolivina vaughani NATLAND, 1938, Bull. Scripps Inst. Oceanog., Tech. ser., vol. 4, p. 146, pl. 5, fig. 11.

Distribution of living specimens of this species shows the maximum frequency at less than 10 fathoms in Todos Santos Bay. The depth range, however, is from 6 to 215 fathoms. Only one specimen is recorded from a depth of 215 fathoms which is at the base of a steep slope and may represent a displacement from shallower water. The species has a wide areal distribution in the immediate area of the bay.

BUCCELLA FRIGIDA (Cushman)
Plate 103, figures 3, 4

Pulvinulina frigida CUSHMAN, 1922, Contr. Can. Biol., p. 12.
Eponides frigida (Cushman), CUSHMAN, 1941, Contr. Cushman Lab. Foram. Res. vol. 17, p. 37, pl. 9, figs. 16, 17.
Bucella frigida (Cushman), ANDERSEN, 1952, Jour. Wash. Acad. Sci., vol. 42, no. 5, p. 144, figs. 4a–6c.

The living depth range of this species is from 6 to 122 fathoms in Todos Santos Bay. Its frequency distribution is fairly constant but it tends to peak around 100 fathoms. Both living and dead specimens have a wide distribution in this area.

BULIMINA AFFINIS d'Orbigny
Plate 102, figure 15

Bulimina affinis D'ORBIGNY, 1840, in DE LA SAGRA, Hist. Phys. Pol. Nat. Cuba, "Foraminiferes," vol. 6, p. 109, pl. 2, figs. 25, 26. See *Globobulimina* spp.

BULIMINA DENUDATA Cushman & Parker
Plate 102, figure 8

Bulimina denudata CUSHMAN & PARKER, 1938, p. 57, pl. 10, figs. 1, 2.

The living specimens of *B. denudata* have a depth range of 19 to 215 fms. in Todos Santos Bay. The frequency distribution shows a definite maximum between 50 and 100 fms. and is skewed toward deeper water.

BULIMINA EXILIS TENUATA (Cushman)
Plate 102, figure 6

Buliminella subfusiformis Cushman var. *tenuata* CUSHMAN, 1927, Bull. Scripps Inst. Oceanog., Tech. ser., vol. 1, p. 149, pl. 2, fig. 9.
Bulimina exilis H. B. Brady var. *tenuata* (Cushman), CUSHMAN & PARKER 1947, U. S. Geol. Surv. Prof. Paper 210 D, p. 124, pl. 28, fig. 29.
Buliminella exilis (H. B. Brady), in BANDY, 1953, Jour. Paleontology, Vol. 27, p. 176, pl. 25, figs. 9a–b.

No living specimens of this species were found in the area studied. It occurred only on the outer end of the long traverse at stations B-138, 140, 141, and 141-1. These spec-

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EXPLANATION OF PLATE 100

FIGS. *1, 2, 3*—*Gaudryina* cf. *G. subglabrata* Cushman & McCulloch. ×46.
4—*Gaudryina arenaria* Galloway & Wissler. ×46.
5—*Textularia* cf. *T. earlandi* Parker. ×46.
6—*Rudigaudryina inepta* Cushman & McCulloch. ×33.
7, 8—*Textularia* cf. *T. schencki* Cushman & Valentine. ×46.
9—*Eggerella advena* (Cushman). ×70.
10, 11—*Goësella flintii* Cushman. ×21.
12, 13—*Miliammina fusca* (H. B. Brady). ×46.
14, 19, 20—*Quinqueloculina* sp. (14, 20) ×46; (19) ×33.
15, 21—*Triloculina* sp. 2 ×46.
16–18—*Triloculina* sp. 1×70.
22, 23—*Sigmoilina* cf. *S. miocenica* Cushman. ×46.
24—*Cornuspira* sp. ×70.
25, 26—*Trochammina kellettae* Thalmann. ×46.
27–29—*Trochammina inflata* (Montagu). ×46.
30, 31—*Trochammina pacifica* Cushman. ×46.

imens are believed to be reworked from ancient sediments outcropping on the continental shelf.

BULIMINA PAGODA Cushman
Plate 102, figure 9

Bulimina pagoda Cushman var. *hebespinata* R. E. & K. C. Stewart, CUSHMAN & MCCULLOCH, 1948, Allan Hancock Pacific Exped., vol. 6, no. 5, p. 244, pl. 30, fig. 6; NATLAND, 1933, Bull. Scripps Inst. Oceanog., Tech. ser., vol. 3, no. 10.

Bulimina pagoda CUSHMAN, 1927, Bull. Scripps Inst. Oceanog., Tech. ser., vol. 1, p. 152, pl. 2, fig. 16.

No living specimens of this species were found in the area studied. It occurs only in samples B-141 and 141-1. B-141-1 at a depth of 1 inch in a core contains a pure Pliocene fauna in a dark siltstone. The occurrence of this species in the Recent sediments at station B-141 is attributed to reworking of the underlying Pliocene siltstones.

BULIMINA SPINIFERA Cushman
Plate 102, figure 7

Bulimina spinifera CUSHMAN, 1927, Bull. Scripps Inst. Oceanog., Tech. ser., vol. 1, p. 151, pl. 2, fig. 15.

For the distribution of this species see *Globobulimina* spp.

BULIMINA SUBACUMINATA Cushman & R. E. Stewart
Plate 102, figure 10

Bulimina subacuminata CUSHMAN & R. E. STEWART, 1931, Trans. San Diego Soc. Nat. Hist., vol. 6, no. 2, p. 65, pl. 5, figs. 2, 3a–b.

No living specimens of this species were found in the area studied. Dead specimens were recorded only from stations B-139, 140, 141, and 141-1. The samples were taken in an area of outcropping Pliocene strata and are considered to be reworked specimens.

BULIMINA SUBAFFINIS Cushman
Plate 102, figure 14

Bulimina subaffinis CUSHMAN, 1921, U. S. Nat. Mus., Bull., 100, vol. 4, p. 166, text figs. 7a, b.

See *Globobulimina* spp.

BULIMINELLA ELEGANTISSIMA (d'Orbigny)
Plate 102, figure 17

Bulimina elegantissima D'ORBIGNY, 1839, Voy. Amer. Merid., vol. 5, pt. 5, "Foraminiferes," p. 51, pl. 7, figs. 13, 14.

Scattered occurrences of living specimens of this species range from 5 to 165 fathoms in Todos Santos Bay. It occurs most abundantly, however, between 10 and 20 fathoms, and the deeper occurrences appear to be displacements from shoaler water.

CANCRIS AURICULA (Fichtel & Moll)
Plate 102, figures 25, 26

Nautilus auricula FICHTEL & MOLL, 1803, Test. Micr., var. a, pl 108, pl. 20, figs. 2a–c; var. b, p. 110, pl. 20, figs. 2d–f.

Living specimens of this species occur at depths of from 30 to 300 fathoms in Todos Santos Bay. It is most abundant between 150 and 200 fathoms and appears to be most characteristic of the depth range 50 to 200 fathoms.

CASSIDULINA CALIFORNICA Cushman & Hughes
Plate 103, figure 25

Cassidulina californica CUSHMAN & HUGHES, 1925, Contr. Cushman Lab. Form. Res., vol. 1, no. 1, p. 12, pl. 2, figs. 1 a–c.

This species was not found living in the area studied. It occurs dead over the area of relict sediments in Todos Santos Bay but is most abundant over or near the outcrops of Pliocene sediments on the continental shelf. It is believed that this species does not represent a part of the living fauna in this area.

CASSIDULINA DELICATA Cushman
Plate 103, figures 28, 29

Cassidulina delicata CUSHMAN, 1927, Bull. Scripps Inst. Oceanog., vol. 1, p. 168, pl. 6, fig. 5.

This species does not occur living shoaler than 250 fathoms in the Todos Santos Bay area. It occurs in all samples deeper than 250 fathoms and shows a slight maximum between 350 and 400 fathoms. Dead specimens of this species are more abundant and occur over a greater depth range than living specimens.

CASSIDULINA LAEVIGATA d'Orbigny
Plate 104, figures 2, 7

Cassidulina laevigata D'ORBIGNY, 1826, Ann. Sci. Nat., vol. 1, p. 282 pl. 15, figs. 4, 5; Modeles, no. 41.

This species does not occur living shallower than 250 fathoms in the area of Todos Santos Bay. It occurs most abundantly between 350 and 400 fathoms but appears to be characteristic of depths greater than 350 fathoms. The dead specimens of this species approximately correspond with the living specimens.

CASSIDULINA LIMBATA
Cushman & Hughes
Plate 103, figure 30

Cassidulina limbata CUSHMAN & HUGHES, 1925, Contr. Cushman Lab. Foram. Res., vol. 1, pt. 1, p. 12, pl. 2, figs. 2a–c.

Living specimens of this species do not occur deeper than 100 fathoms in Todos Santos Bay. They are most abundant between 20 and 30 fathoms, with the greatest abundance at station B-83 in 26 fathoms. Dead specimens occur as deep as 490 fathoms in the vicinity of outcropping Pliocene strata but do not appear to reflect a living population at this depth.

CASSIDULINA SUBGLOBOSA
H. B. Brady variants
Plate 103, figure 21

Cassidulina subglobosa H. B. BRADY, 1881, Quart. Jour. Micr. Sci., n. ser., vol. 21, pt. III, p. 60; ———, 1884, Rep't. Voy. *Challenger*, Zool., vol. 9, pl. 54, figs. 17a–c.

Living specimens of this species occur from 5 to 150 fathoms but are most abundant between 20 and 30 fathoms. Dead specimens and the variety *G. subglobosa quadrata* constitute large percentages of dead populations in the areas of relict sediments in Todos Santos Bay and occur as deep as 490 fathoms. These widespread occurrences of dead specimens appear to reflect, at least in part, relict and/or fossil faunas and do not represent living populations.

CASSIDULINA TORTUOSA
Cushman & Hughes
Plate 103, figures 26, 27

Cassidulina tortuosa CUSHMAN & HUGHES, 1925, Contr. Cushman Lab. Foram. Res., vol. 1, pt. 1, p. 14, pl. 2, figs. 4a–c.

This species only occurs living at depths shoaler than 50 fathoms in Todos Santos Bay, and is most abundant between 40 and 50 fathoms. Dead specimens are very abundant in the areas of relict sediments but apparently do not reflect similar abundances in living populations. The species occurs dead down to 215 fathoms in areas of considerable relief, and such occurrences apparently indicate displacement from shallow water.

CASSIDULINA sp.
Plate 104, figures 3, 4

This species is similar to *C. islandica* Norvang var. *minuta* Norvang, but differs in that the test is more compressed.

This form occurs living in the area of Todos Santos Bay from 20 to 300 fathoms with its maximum abundance between 40 and 50 fathoms. Dead specimens occur as deep as 490 fathoms but do not appear to reflect living populations at this depth.

CASSIDULINOIDES sp.
Plate 104, figure 1

This species is similar to *C. simplex* Cushman & Todd from the Miocene of Jamaica but is broader, more compressed, and generally larger.

It is recorded from only one station at 155 fathoms in Todos Santos Bay.

CHILOSTOMELLA OVOIDEA Reuss
Plate 104, figures 6, 15

Chilostomella ovoidea REUSS, 1850, Deukschr. Akad. Wiss., vol. 1, p. 380, pl. 48, fig. 12.

The population counts of *C. ovoidea* include a smaller species which is similar to *C. mediterranensis* Cushman & Todd (Pl. 104, fig. 15).

Living specimens of this species have a wide range of occurrence between 50 and 600 fathoms. Its frequency distribution shows a definite maximum between 350 and 400 fathoms. Dead specimens also occur over a wide depth range but are generally most abundant deeper than 250 fathoms

CIBICIDES FLETCHERI
Galloway & Wissler
Plate 104, figures 11, 12

Cibicides fletcheri GALLOWAY & WISSLER, 1927, Journ. Paleontology, vol. 1, p. 64, pl. 10, figs. 8, 9.

The living specimens of this species are very common in Todos Santos Bay and constitute large percentages of the living populations in the marginal bay facies. Isolated specimens are found as deep as 215 fathoms, but the species occurs most abundantly between 10 and 30 fathoms. This species likewise constitutes large percentages of the dead populations in the marginal bay facies but occurs as deep as 380 fathoms.

It is common in the late Tertiary sediments of California, and the wide distribution of dead specimens may indicate reworking of "fossil" strata.

CIBICIDES GALLOWAYI
Cushman & Valentine
Plate 104, figures 16, 21

Cibicides gallowayi CUSHMAN & VALENTINE, 1930, Contr. Dept. Geol. Stanford Univ., vol. 1, no. 1, p. 30, pl. 10, figs. 4a–c.

Living specimens of this species occur rarely between 5 and 35 fathoms in Todos Santos Bay. Dead specimens occur as deep as 215 fathoms but apparently indicate displacement from shoaler water.

CIBICIDES MCKANNAI
Galloway & Wissler
Plate 104, figures 13, 14

Cibicides mckannai GALLOWAY & WISSLER, 1927, Journ. Paleontology, vol. 1, p. 65, pl. 10, figs. 5, 6.

Living specimens of this species range from 20 to 100 fathoms but occur most abundantly between 30 and 50 fathoms. Dead specimens occur as deep as 490 fathoms, but these deeper occurrences may reflect reworking of fossil faunas as this species is common in both the Pliocene and Pleistocene of California.

CIBICIDES SPIRALIS Natland
Plate 104, figures 8, 9

Cibicides spiralis NATLAND, 1938, Bull. Scripps Inst. Oceanog., Tech. ser., vol. 4, no. 5, p. 151, pl. 7, figs. 7a–c.

This species was not found living in the area studied. It occurs dead in several deep stations near outcrops of Pliocene strata and may reflect reworking of these older sediments.

CIBICIDINA NITIDULA Bandy
Plate 104, figures 17–19

Cibicidina basiloba (Cushman) var. *nitidula* BANDY, 1953, Jour. Paleontology, vol. 27, p. 178, pl. 22, figs. 3a–c.

This species occurs living between 10 and 50 fathoms in relatively low frequencies. It is distributed generally over the area of coarse sediments in Todos Santos Bay and is commonly attached to the larger sediment particles and shell fragments. Dead specimens occur as deep as 215 fathoms at the base of the steep scarp between the Todos Santos Islands and Punta Banda and apparently have been displaced from shoaler water.

CORNUSPIRA sp.
Plate 100, figure 24

This species was encountered rarely in this study, and not enough specimens were were found to warrant an identification.

Living specimens occur rarely from 7 to 110 fathoms in Todos Santos Bay. Dead specimens occur more abundantly over approximately the same depth range.

DISCORBIS spp.
Plate 102, figures 27–29

The species of *Discorbis* encountered in this study were extremely variable and graded into one another. As they all occurred together, they were not differentiated. The most common and most typical of these forms are figured on Plate 102.

Living specimens occur from 5 to 40 fathoms in Todos Santos Bay, with one isolated occurrence at 110 fathoms. Dead specimens are very abundant and constitute large percentages of the dead populations.

DYOCIBICIDES BISERIALIS
Cushman & Valentine
Plate 104, figures 22, 23

Dyocibicides biserialis CUSHMAN & VALENTINE, 1930, Contr. Dept. Geol. Stanford Univ., vol. 1, no. 1, p. 31, pl. 10, figs. 1, 2a–b.

This species was described from off the coast of California and has been reported from 10 to 12 fms. It is also reported from the coast of Washington by Cushman & Todd (1947). *D. perforata* Cushman & Valentine was encountered rarely in this study and is included in the population counts of *D. biserialis*.

Living specimens of this species do not occur deeper than 30 fathoms in Todos Santos Bay and are most commonly attached to large sediment particles and shell fragments. Dead specimens occur as deep as 215 fathoms and apparently indicate displacement from shallow water.

DISCORINOPSIS cf. D. AGUAYOI
(Bermudez)
Plate 103, figures 6, 7

Discorbis aguayoi BERMUDEZ, 1935, Mem. Soc. Cubana, Hist. Nat., vol. 9, no. 3, p. 204, pl. 15, figs. 10–14.

Discorinopsis vadescens Cushman & Bronnimann, 1948, Contr. Cushman Lab. Foram. Res., vol. 24, pt. 1, p. 20, pl. 4, figs. 9, 10.

This species was encountered in only three stations in the marsh subfacies in the Estero de Punta Banda. It was not found living in the area studied.

Eggerella advena (Cushman)
Plate 100, figure 9

Verneuilina advena Cushman, 1922, Contr. Canadian Biol., no. 9, p. 141.
Verneuilina polystropha Cushman [not Reuss], 1920, Rept. Canadian Arctic Exped., vol. 9, p. 8, pl. 1, fig. 5.

According to Parker (1952, p. 404), "This species was first referred to *Verneuilina polystropha* Cushman, 1920 . . . [and] the Arctic specimens should form the basis for the conception of the species." The specimens from Todos Santos Bay were compared with Gulf of Mexico and Cape Cod Bay specimens and some from the Canadian Arctic. They are smaller, more sharply tapered, and generally more coarsely arenaceous. Some appear to be multiserial in the initial chambers and are thus referred to this species.

Living specimens of this species occur from 5 to 100 fathoms in Todos Santos Bay with their maximum abundance shallower than 10 fathoms. Dead specimens occur as deep as 215 fathoms along with other displaced shallow-water species and are generally abundant in most of the bay samples.

Ehrenbergina compressa Cushman
Plate 104, figures 5, 10

Ehrenbergina compressa Cushman, 1927, Bull. Scripps Inst. Oceanog., Tech. ser., vol. 1, no. 10, p. 168, pl. 6, fig. 7.

This species does not occur living in the area of Todos Santos Bay. Dead specimens were found at three stations (266, 375, and 480 fathoms) over or near outcrops of Pliocene strata and are thought to represent reworking of the Pliocene sediments.

Elphidium crispum (Linné)
Plate 101, figure 11

Nautilus crispus Linné, 1758, Syst. Nat., ed. 10, p. 709; ed. 13 (Gmelins), 1788, p. 3370 (Plancus de Conch), p. 10, pl. 1, fig. 2.

This species has not been found living in the area of Todos Santos Bay. Dead specimens occur in the area of relict sediments and are believed to be part of the associated relict fauna which represents a previous environment of deposition.

Elphidium spinatum
Cushman & Valentine
Plate 101, figure 12

Elphidium spinatum Cushman & Valentine, 1930, Contrib. Dept. Geol. Stanford Univ., vol. 1, no. 1, p. 31, pl. 6, figs. 1a–2.

This species was found living at depths shallower than 20 fathoms in Todos Santos Bay. Dead specimens were recorded from several stations but in low frequencies. Dead specimens also were encountered at a few stations in the channels of the Estero de Punta Banda.

Elphidium translucens Natland
Plate 101, figure 7

Elphidium translucens Natland, 1938, Bull. Scripps Inst. Oceanog., Tech. ser., vol. 4, no. 5, p. 144, pl. 5, figs. 3, 4.

Living specimens of this species do not occur deeper than 30 fathoms in Todos Santos Bay. They occur most abundantly between 0 and 10 fathoms. Dead specimens occur at several stations in the bay to depths of 215 fathoms. The isolated occurrences at 215 fathoms appear to be displaced from shallow water. Dead specimens also occur in a few stations in the Estero de Punta Banda.

Elphidium tumidum Natland
Plate 101, figures 8, 9

Elphidium tumidum Natland, 1938, Bull. Scripps Inst. Oceanog., Tech. ser., vol. 4, no. 5, p. 144, pl. 5, figs. 5, 6.

Living specimens of this species were recorded only from stations shallower than 30 fathoms in Todos Santos Bay. They occur most abundantly between 10 and 20 fathoms. Living specimens were also recorded from both the marsh and channel subfacies in the Estero de Punta Banda. Dead specimens are common over approximately the same depth range as the living individuals. Dead specimens were very abundant in the channel stations of the Estero de Punta Banda.

ELPHIDIUM sp.
Plate 101, figures 10, 15

This species is similar to *E. galvestonensis* Kornfeld but differs from that species in that the umbilical plug is smaller and the test generally is more compressed.

Living specimens of this species have been found only in the marsh subfacies of the Estero de Punta Banda. Dead specimens occur commonly in the channel stations of the estero.

EPISTOMINELLA SMITHI
(R. E. & K. C. Stewart)
Plate 103, figures 22, 23

Pulvinulinella smithi R. E. & K. C. STEWART, 1930, Journ. Paleontology, vol. 4, p. 70, pl. 9, fig. 4.

This species occurs living between 200 and 400 fathoms in the area of Todos Santos Bay in relatively low numbers. Only five living specimens were found. Dead specimens occur most abundantly in the offshore traverse at 200 to 400 fathoms.

EPONIDES cf. E. REPANDUS
(Fichtel & Moll)
Plate 103, figures 8, 9

Nautilus repandus FICHTEL & MOLL, 1798, Test. Micro., p. 35, pl. 3, figs. a–d.

Some of the specimens included in the population counts of *E.* cf. *E. repandus* probably belong in the genus *Poroeponides.* These specimens were not differentiated due to the paucity of specimens encountered in this study.

This species did not occur living in the present area. Dead specimens were common in the immediate vicinity of relict sediments and are believed to represent a previous environment.

EPONIDES SUBTENERA
(Galloway & Wissler)
Plate 103, figures 1, 2

Rotalia subtenera GALLOWAY & WISSLER, 1927, Jour. Paleontology, vol. 1, no. 1, p. 60, pl. 10, fig. 4.

This species was not found living in the Todos Santos Bay area. Dead specimens occur in samples of the offshore traverse in the area of outcropping Pliocene sediments and are thought to be reworked from the Pliocene fauna.

EPONIDES UMBONATUS (Reuss)

Rotalina umbonata REUSS, 1851, Zeitsch. deutsch. geol. Ges., Bd. 3, p. 75, pl. 5, figs. 35a–c.

This species was not found living in the area of Todos Santos Bay. It occurred dead only at station B-141 over outcropping Pliocene sediments and is thought to be a reworked species.

GAUDRYINA ARENARIA
Galloway & Wissler
Plate 100, figure 4

Gaudryina arenaria GALLOWAY & WISSLER, 1927, Jour. Paleontology, vol. 1, p. 68, pl. 11, fig. 5.

This species occurs living in low frequencies between 20 and 150 fathoms in Todos Santos Bay. Its frequency distribution shows no marked maximum within this depth range. Dead specimens are recorded as deep as 215 fathoms.

GAUDRYINA cf. G. SUBGLABRATA
Cushman & McCulloch
Plate 100, figures 1–3

Gaudryina subglabrata CUSHMAN & MCCULLOCH, 1939, Allan Hancock Pacific Exped., vol. 6, no. 1, p. 92, pl. 8, figs. 5–7.

Living specimens of this species occur between 10 and 40 fathoms in Todos Santos Bay. The maximum abundance is between 10 and 20 fathoms, and dead specimens occur as deep as 375 fathoms in the samples of the offshore traverse.

GLOBOBULIMINA spp.
Plate 102, figures 13–16

Globobulimina sp. b HÖGLUND, 1947, Zool. Bidrag Fran Uppsala, Bd. 26, p. 245, pl. 21, figs. 2, 7; pl. 22, fig. 3; text figs. 238, 242.

The reasons for grouping several species in this population count are given in the discussion of the genus *Globobulimina* by Höglund (1947). This group includes species that have been identified from off the west coast of North America as *G. pacifica* Cushman, *Bulimina* (*Desinobulimina*) *auriculata* Bailey, *B. affinis* d'Orbigny, *B. subaffinis* Cushman, and what has been called *B. ovata* and *B. ovula* by Natland (1933) and Crouch (1952). *B. spinifera* Cushman has been included in this count as it only occurs rarely in the sediment samples.

Living specimens of this group of Foraminifera occur from 30 fathoms to 600 fathoms. Their frequency distribution shows a marked maximum between 100 and 150 fathoms. They occur commonly at most stations deeper than 100 fathoms. Dead specimens are common over approximately the same depth range as living specimens.

GOËSELLA FLINTII Cushman
Plate 100, figures 10, 11

Goësella flintii CUSHMAN, 1936, Cushman Lab. Foram. Res., Spec. Publ. 6, p. 34, pl. 5, fig. 8.

Living specimens occur from 20 to 400 fathoms in Todos Santos Bay. The frequency (Text-fig. 21) shows a bimodal distribution which may indicate that it includes two closely related groups. The distribution of the dead specimens corresponds roughly with that of the living.

GYROIDINA ALTIFORMIS
R. E. & K. C. Stewart
Plate 103, figures 10, 11

Gyroidina soldanii var. *altiformis* R. E. & K. C. STEWART, 1930, Jour. Paleontology, vol. 4, no. 1, p. 67, pl. 9, figs. 2a–c.

No living specimens have been recorded from the area studied. Dead specimens occur rarely in the area of relict sediments in Todos Santos Bay and near the outcropping Pliocene strata on the continental shelf. It is believed that this species does not occur living in this area but represents a relict and/or residual species.

HÖGLUNDINA ELEGANS (d'Orbigny)
Plate 103, figures 5, 14

Rotalia (*Turbinulina*) *elegans* D'ORBIGNY, 1826, Ann. Sci. Nat., vol. 7, p. 276, no. 54.
Pulvinulina elegans Parker, JONES & BRADY, 1871 Ann. Mag. Nat. Hist., ser. 4, vol. 8, p. 174, pl. 13, fig. 142.
Epistomina elegans (d'Orbigny), CUSHMAN, 1931, U. S. Nat. Mus., Bull. 104, pt. 8, p. 65, pl. 13, fig. 6.

Living representatives of this species do not occur shallower than 400 fathoms in the area studied. They generally occur in low frequencies as can be seen from Text-figure 23. Dead specimens occur rarely in depths corresponding to the living distribution.

JADAMMINA POLYSTOMA
Bartenstein & Brand
Plate 101, figures 4, 5

Jadammina polystoma BARTENSTEIN & BRAND, 1938, Senckenbergiana, Bd. 20, p. 381, text. figs. 1a–c, 2a-l, 3.
Trochammina macrescens H. B. Brady, PHLEGER & WALTON, 1950, Am. Jour. Sci., vol. 248, p. 281, pl. 2, figs. 12, 13.

Living specimens of this species were recorded only from the marsh subfacies of the Estero de Punta Banda. Dead specimens occur in the channel subfacies but neither living nor dead specimens were found outside of the Estero de Punta Banda.

LABROSPIRA cf. L. ADVENA (Cushman)
Plate 99, figures 15–17

Haplophragmoides advena CUSHMAN, 1925, Contr. Cushman Lab. Foram. Res., vol. 1, pt. 2, p. 38, pl. 6, figs. 1a, b.

Living specimens of this species do not occur deeper than 50 fathoms in Todos Santos Bay. The frequency distribution shows a maximum between 40 and 50 fathoms. This distribution of the dead specimens roughly corresponds with that of the living specimens.

LABROSPIRA cf. L. COLUMBIENSIS (Cushman)
Plate 99, figures 13, 18, 19

Haplophragmoides columbiense CUSHMAN, 1925, Contr. Cushman Lab. Foram. Res., vol. 1, pt. 2, p. 39, pl. 6, figs. 2a, b.

Living specimens of this species occur shallower than 300 fathoms in Todos Santos Bay. They occur most abundantly shallower than 100 fathoms with a maximum between 10 and 20 fathoms. Dead specimens are common in the samples in Todos Santos Bay and their distribution corresponds approximately with the living distribution.

LAGENIDAE

The species of this family were not differentiated and are included in one count. They have a limited distribution and do not appear to be significant ecological indicators.

LAMELLODISCORBIS sp.
Plate 102, figures 30, 31

This species, which occurs only near the head of the Estero de Punta Banda, is placed in *Lamellodiscorbis* Bermudez (1952) because the plate of the ventral side is simple, is restricted to the umbilical area, and has secondary apertures along the sutures. It differs from the closely related genus

Discorinopsis in the location of the plate and the secondary apertures.

This species was not found living in the area studied. It occurs dead at only one station in the Estero de Punta Banda, and was not found elsewhere in the area.

LOXOSTOMA PSEUDOBEYRICHI (Cushman)
Plate 102, figure 20

Bolivina pseudobeyrichi CUSHMAN, 1926, Contr. Cushman Lab. Foram. Res., vol. 2, pt. 2, p. 45; ——, 1927, Bull. Scripps Inst. Oceanog., Tech. ser., vol. 1, p. 156, pl. 3, fig. 7.

Living specimens were not found shoaler than 350 fathoms in the Todos Santos Bay area. The frequency distribution shows no marked maximum. This distribution of the dead specimens generally corresponds with that of the living specimens.

MILIAMMINA FUSCA (H. B. Brady)
Plate 100, figures 12, 13

Quinqueloculina fusca H. B. BRADY, 1870, Ann. Mag. Nat. Hist., ser. 4, vol. 6, p. 47, (286), pl. 11, figs. 2a–c.

Living specimens of this species occur abundantly in all the subfacies of the Estero de Punta Banda and rarely in a few samples from Todos Santos Bay. The distribution of the dead specimens of this species generally corresponds with that of the living specimens.

MILIOLIDAE

The Miliolidae were not differentiated, with the exception of *Quinqueloculina* sp., *Sigmoilina* cf. *S. miocenica*, and *Triloculina* sp. 1, sp. 2, and sp. 3. They are most abundant in the area of relict sediments around the Todos Santos Islands and include many species not represented by living forms.

NONIONELLA BASISPINATA
(Cushman & Moyer)
Plate 101, figures 16, 17

Nonion pizarrensis Berry var. *basispinata* CUSHMAN & MOYER, 1930, Contr. Cushman Lab. Foram. Res., vol. 6, p. 54, pl. 7 figs. 18a, b.

Living specimens of this species are restricted to depths shoaler than 150 fathoms in Todos Santos Bay. The frequency distribution shows a marked maximum between 40 and 50 fathoms. The species occurs most abundantly shoaler than 50 fathoms. Dead specimens are common in most of the bay samples and occur to depths of 380 fathoms.

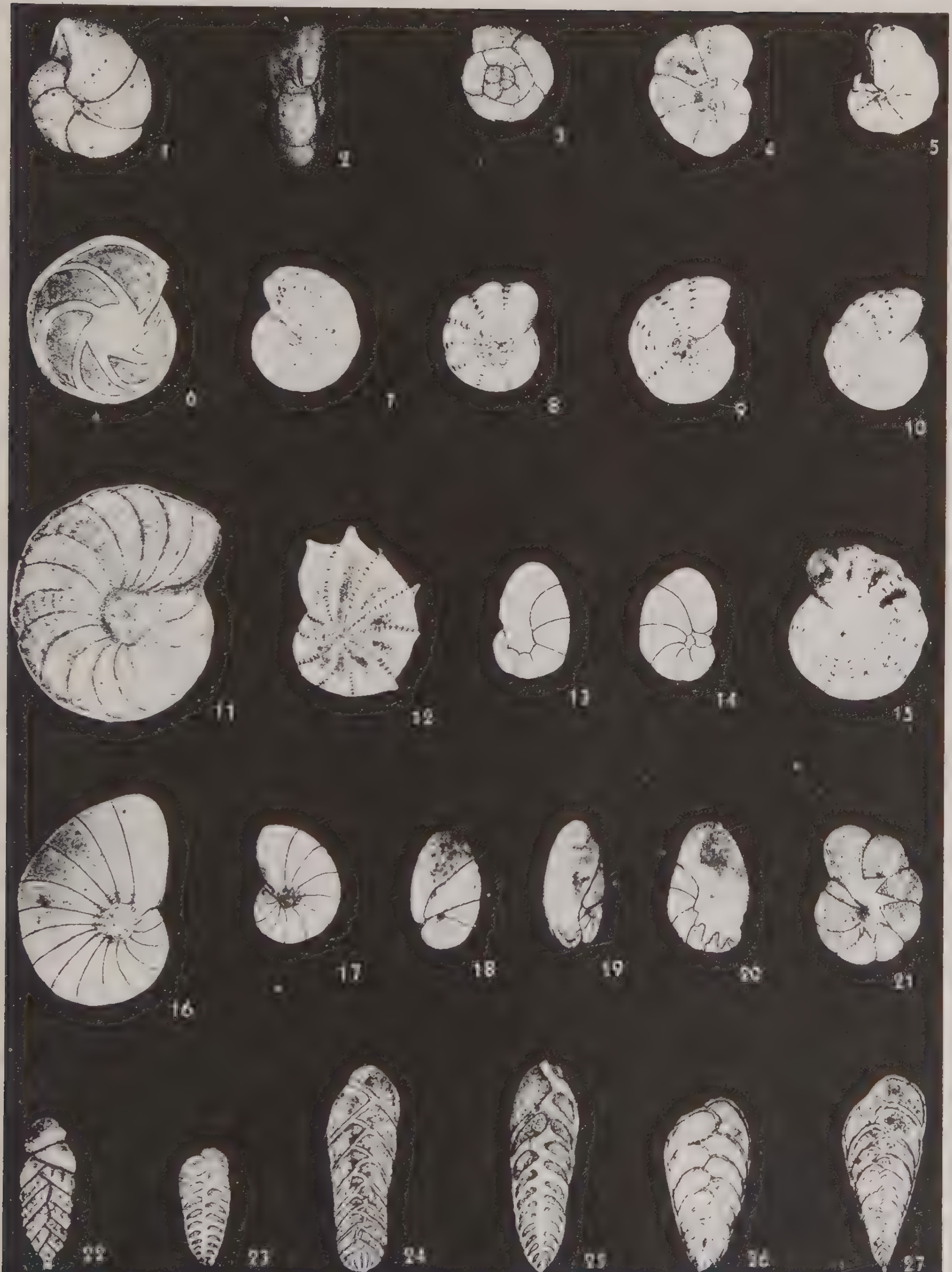
NONIONELLA MIOCENICA STELLA
Cushman & Moyer
Plate 101, figures 13, 14

Nonionella miocenica Cushman var. *stella* CUSHMAN & MOYER, 1930, Contr. Cushman Lab. Foram. Res., vol. 6, p. 56, pl. 7, figs. 17a–c.

Living specimens of this species do not occur deeper than 250 fathoms in Todos Santos Bay. The frequency distribution (Text-fig. 20) shows a marked maximum between 30 and 40 fathoms, and the species occurs most abundantly between 10 and 100 fathoms. It is one of the most common living species encountered in this study. Dead specimens commonly occur over the same depth range as do the living specimens but are found to depths of 490 fathoms.

EXPLANATION OF PLATE 101

FIGS. *1–3*—*Arenoparrella mexicana* (Kornfeld). ×70.
4, 5—*Jadammina polystoma* Bartenstein & Brand. (4)×70; (5)×46.
6—*Robulus* sp. ×33.
7—*Elphidium translucens* Natland. ×46.
8, 9—*Elphidium tumidum* Natland. ×46.
10, 15—*Elphidium* sp. ×46.
11—*Elphidium crispum* (Linné). ×46.
12—*Elphidium spinatum* Cushman & Valentine. ×46.
13, 14—*Nonionella miocenica stella* Cushman & Moyer. ×46.
16, 17—*Nonionella basispinata* (Cushman & Moyer). ×46.
18–20—*Nonionella* sp. ×70.
21—*Astrononion stellatum* Cushman & Edwards. ×46.
22—*Bifarina hancocki* Cushman & McCulloch. ×46.
23—*Bolivina vaughani* Natland. ×70.
24, 25—*Bolivina spissa* Cushman. ×46.
26, 27—*Bolivina argentea* Cushman. ×33.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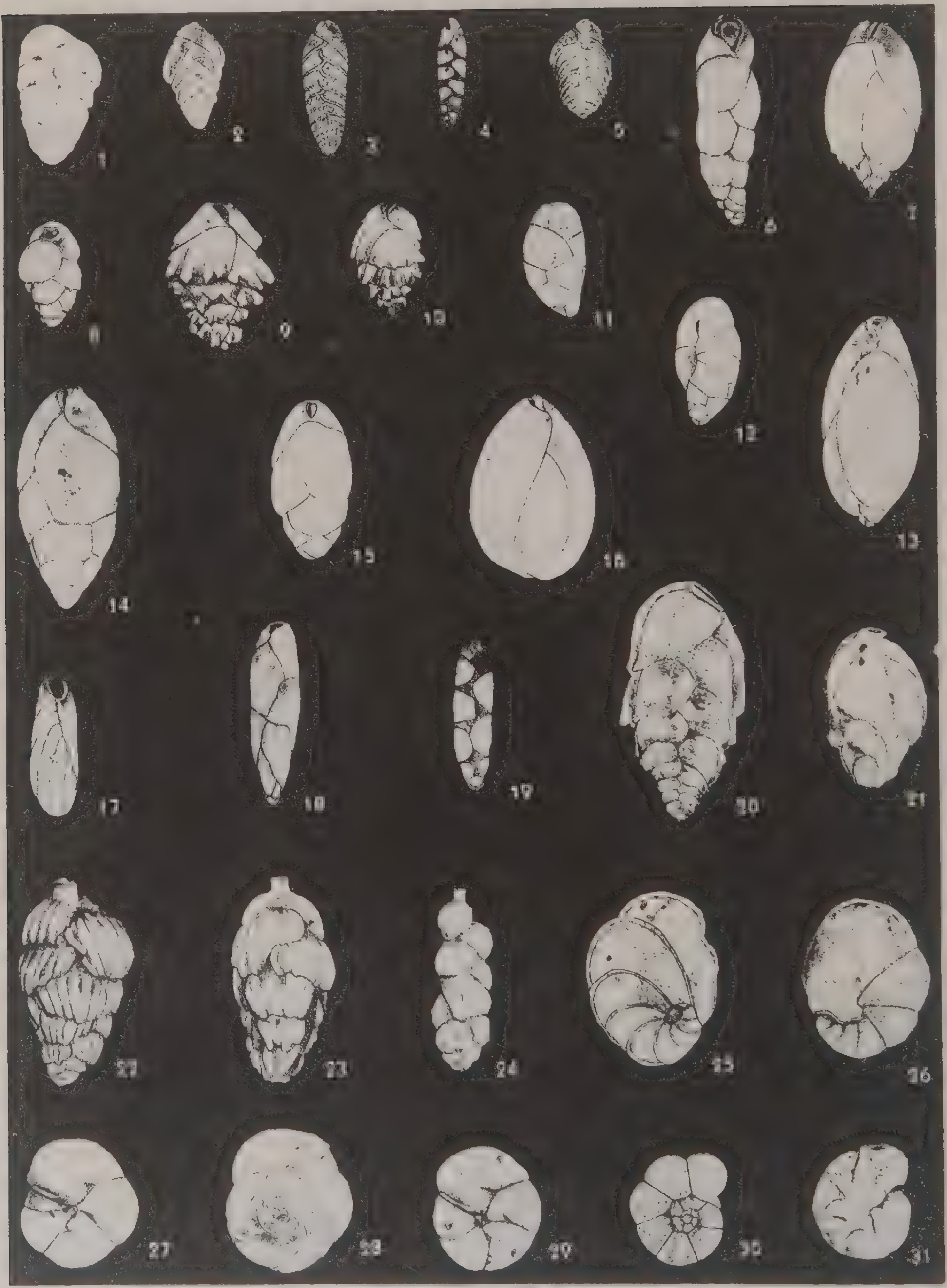
Walton, Living Foraminifera from Baja California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Walton, Living Foraminifera from Baja California

NONIONELLA sp.
Plate 101, figures 18–20

This species is very similar to *N. basiloba* (Cushman & McCulloch, 1940) but the last chamber extends down to the base of the periphery in long finger-like extensions.

The frequency distribution of the living specimens of this species shows a bimodal tendency. It occurs living from 30 to 400 fathoms but population peaks occur between 100 and 150 fathoms and 350 and 400 fathoms. This distribution suggests that two closely related species or varieties have been included in the population counts. Dead specimens are most common in water depths greater than 200 fathoms. This species is generally small and the young forms are difficult to distinguish from young representatives of *N. miocenica stella*. It is possible that the population maximum between 100 and 150 fathoms may include young forms of *N. miocenica stella*.

PLANORBULINA MEDITERRANENSIS d'Orbigny

Planorbulina mediterranensis D'ORBIGNY, 1826, Ann. Sci. Nat., vol. 7, p. 280, no. 2, pl. 14, figs. 4–6.

A few living specimens of this species were found attached to shell fragments and larger sediment particles in approximately 25 fathoms. The distribution of these commonly attached forms is controlled by the size of the sediment particles, and the species occurs only in the areas of coarser sediments. The distribution of the dead specimens corresponds with that of the living.

PLANULINA cf. P. ARIMINENSIS d'Orbigny
Plate 104, figures 27, 28

Planulina ariminensis D'ORBIGNY, 1826, Ann. Sci. Nat., vol. 7, no. 1, pl. 14, figs. 1–3 bis; Modeles, no. 49.

No living specimens of this species were found in the area studied. Dead specimens are most commonly associated with areas of relict and "fossil" sediments, and it is believed that they came from those sediments.

PLANULINA EXORNA
Phleger & Parker
Plate 104, figures 24, 25, 29, 30

Planulina exorna PHLEGER & PARKER, 1951, Geol. Soc. America, Mem. 46, pt. 2, p. 32, pl. 18, figs. 5a,b, 6a,b, 7a,b, 8a,b.

Planulina ariminensis GALLOWAY & WISSLER, 1927, Jour. Paleontology, vol. 1, p. 66, pl. 11, fig. 2.

Planulina ornata (d'Orbigny), CUSHMAN & VALENTINE [part], 1930, Contr. Dept. Geol., Stanford Univ., vol. 1, no. 1, p. 29, pl. 9, figs. 4a–c [not 2a–c].

EXPLANATION OF PLATE 102

FIGS. *1*—*Bolivina* cf. *B. pseudoplicata* Heron-Allen & Earland. ×70.
2—*Bolivina minuta* Natland. ×70.
3—*Bolivina striatella* Cushman. ×46.
4—*Bolivina pacifica* Cushman & McCulloch. ×46.
5—*Bolivina acuminata* Natland. ×46.
6—*Bulimina exilis tenuata* (Cushman). ×46.
7—*Bulimina spinifera* Cushman. ×46.
8—*Bulimina denudata* Cushman & Parker. ×46.
9—*Bulimina pagoda* Cushman. ×46.
10—*Bulimina subacuminata* Cushman & Stewart. ×46.
11, 12—*Robertina charlottensis* Cushman. ×46.
13, 16—*Globobulimina* spp. ×46.
14—*Bulimina subaffinis* Cushman. ×46.
15—*Bulimina affinis* d'Orbigny. ×25.
17—*Buliminella elegantissima* (d'Orbigny). ×70.
18—*Virgulina bramletti* Galloway & Morrey. ×33.
19—*Virgulina seminuda* Natland. ×46.
20—*Loxostoma pseudobeyrichi* (Cushman). ×46.
21—*Angulogerina carinata* Cushman. ×33.
22, 23—*Uvigerina peregrina* Cushman; variants. ×46.
24—*Uvigerina senticosa* Cushman. ×46.
25, 26—*Cancris auricula* (Fichtel & Moll). ×33.
27–29—*Discorbis* spp. ×46.
30, 31—*Lamellodiscorbis* sp. ×46.

Planulina depressa (d'Orbigny), NATLAND, 1933, Bull. Scripps Inst. Oceanog., Tech. ser., vol. 3, no. 10.

Planulina ornata (d'Orbigny) ? var., CUSHMAN & GRAY, 1946, Cushman Lab. Foram. Res., Spec. Publ. no. 19, p. 44, pl. 9, figs. 9–12.

This species was originally described from the northwest Gulf of Mexico, where it occurs in depths of less than 100 m. Specimens have been compared with type material and appear to be the same species. It is an extremely variable species, and many of the characteristics present in the young forms, e.g., the flat periphery and the thick prominent sutures, are lost in the adult specimens. The end members of this series are quite different, but an intergrading series can be found between the two.

Living specimens of this species are restricted to depths shallower than 100 fathoms in the Todos Santos Bay area. The frequency shows a maximum between 40 and 50 fathoms (Text-fig. 21), and the geographic distribution is characteristic of the marginal bay facies. Dead specimens have a wide distribution and occur as deep as 490 fathoms. The species is common in the Pliocene and Pleistocene of California and the deeper occurring specimens may be reworked.

POLYMORPHINIDAE

The Polymorphinidae were not differentiated in this study. The most abundant genus in the area of Todos Santos Bay is *Guttulina*.

PROTEONINA ATLANTICA Cushman
Plate 99, figure 1

Proteonina atlantica CUSHMAN, 1944, Cushman Lab. Foram. Res., Spec. Publ. 12, p. 5, pl. 1, fig. 4.

Living specimens occur over a wide depth range from 5 to 250 fathoms in Todos Santos Bay. The species is most common shallower than 100 fathoms, however, and its frequency distribution shows a maximum between 20 and 40 fathoms. The distribution of the dead specimens corresponds generally with that of the living specimens.

PROTEONINA sp.
Plate 99, figures 2, 3

This small species has been placed in the genus *Proteonina* because it has a single undivided chamber, the chamber wall is chitinous, and it is covered by small detrital particles, mostly mica. It is extremely fragile and seldom survives the drying process. Most of the dead counts were made from wet samples.

The frequency distribution of the living specimens (Text-fig. 23) is biomodal. This fact suggests that more than one closely related form has been included in the count. Also, a similar species is common in the marsh subfacies of the Estero de Punta Banda.

PULLENIA SALISBURYI
R. E. &. K. C. Stewart
Plate 104, figure 20

Pullenia salisburyi R. E. & K. C. STEWART, 1930, Jour. Paleontology, vol. 4, no. 1, p. 72, pl. 8, fig. 2.

Living specimens of this species are rare in Todos Santos Bay area but occur most commonly at approximately 200 fathoms. Dead specimens also are rare but occur to depths of 490 fathoms.

QUINQUELOCULINA sp.
Plate 100, figures 14, 19, 20

This species is a finely costate form with a single well-developed tooth. Living specimens are restricted to depths shallower than 20 fathoms and occur most abundantly in the 5 to 10 fathom depth range. Dead specimens are also restricted to this narrow depth range. A few living specimens were also found in the channel subfacies in the Estero de Punta Banda.

RECURVOIDES spp.
Plate 99, figures 12, 14

This group of specimens probably includes two closely related species. The shallower one is similar to *R. turbinatus* (H. B. Brady) from the Gulf of Maine and the Greenland Arctic (Phleger, 1952a).

The frequency distribution of the living specimens of these species is shown in Text-figure 22. It shows a bimodal distribution which would be characteristic of two superimposed distributions. There is one maximum shallower than 100 fathoms and one between 250 and 300 fathoms. Most of the dead specimens correspond with the shallower maximum (less than 100 fathoms).

REOPHAX AGGLUTINATUS Cushman
Plate 99, figure 10

Reophax agglutinatus CUSHMAN, 1913, Proc. U. S. Mus., vol. 44, p. 637, pl. 79, fig. 6; ——, 1920, U. S. Nat. Mus., Bull. 104, pt. 2, p. 9, pl. 2, figs. 4, 5; ——, 1921, U. S. Nat. Mus., Bull. 100, vol. 4, p. 73, pl. 14, figs. 2a, b; ——, 1932, U. S. Nat. Mus., Bull. 161, vol. 4, pt. 1, p. 4, pl. 1, figs. 1–3.

Very few living specimens were found in the area studied; they came from two stations in 96 and 125 fathoms. Dead specimens are much more common than living individuals and occur in both shallower and deeper water.

REOPHAX CURTUS Cushman
Plate 99, figure 9

Reophax curtus CUSHMAN, 1920, U. S. Nat. Mus., Bull. 104, pt. 2, pl. 2, figs. 2, 3.

Parker (1952) discusses this species and concludes that it includes *R. subfusiformis* Earland and *R. subfusiformis* Earland emend. Höglund, 1947.

Living specimens in the Todos Santos Bay area occur over a depth range between 10 and 50 fathoms with a marked maximum between 20 and 30 fathoms. The species is one of the most common forms in the middle bay facies. The distribution of dead specimens generally corresponds with that of living specimens.

REOPHAX GRACILIS (Kiaer)
Plate 99, figure 5

Nodulina gracilis KIAER, 1900, Rept. Nor. Fish Mar. Invest., vol. 1, no. 7, p. 24, 2 text figs.

Living specimens of this species have a rather wide distribution in this area; they range from 10 to 400 fathoms and are most common between 50 and 100 fathoms. Dead specimens appear to be most common shallower than 100 fathoms, but they are very fragile and may be lost in the drying process.

REOPHAX HORRIDA Cushman
Plate 99, figure 8

Reophax horrida CUSHMAN, 1912, Proc. U. S. Nat. Mus., vol. 42, pl. 28, figs. 3, 4.

This species has been reported from off Borneo in 890 and 569 fathoms. No other record in the Pacific is known to the author.

Living specimens range from 50 to 400 fathoms off Todos Santos Bay. The frequency distribution shows a marked maximum between 300 and 350 fathoms. The test of this species is very fragile and few dead specimens were found in the samples studied. The only dead specimens recorded are from 275 fathoms.

REOPHAX SCORPIURUS Montfort
Plate 99, figure 4

Reophax scorpiurus MONTFORT, 1808, Conch. Syst., vol. 1, p. 330.

Living specimens of this species range from 5 to 100 fathoms in the Todos Santos Bay area. Its frequency distribution shows a well-developed maximum between 20 and 40 fathoms (Text-fig. 21), and it is generally most abundant from 20 to 50 fathoms. It is one of the most abundant bay species, and its distribution is characteristic of the middle bay facies. The distribution of the dead specimens of this species corresponds generally with that of the living specimens.

REOPHAX sp. 1
Plate 99, figure 7

This small species is very fragile and generally does not survive drying. Its average length is approximately 0.5 to 0.7 mm., and the width of its largest chamber averages 0.1 to 0.2 mm. It commonly has 6 to 8 chambers composed of chitin, mica flakes, and small agglutinated Foraminifera shells.

Living specimens of this species are limited to depths greater than 300 fathoms and are most abundant between 350 and 400 fathoms.

REOPHAX sp. 2
Plate 99, figure 6

This small species does not occur outside of the Estero de Punta Banda. It contains about 7 or 8 chambers, is finely arenaceous, and has a round aperture. No living specimens of this species were found, but it is common in the channel subfacies of the estero. It ranges in length from 0.14 to 0.36 mm.

RHABDAMMINA cf. R. ABYSSORUM M. Sars

Rhabdammina abyssorum M. SARS, 1868, Forh. Selsk. Christiania, p. 248 [nomen nudum]; ——, 1868, in W. B. CARPENTER, Ann. Mag. Hist. Nat., ser. 4, vol. 4, p. 288.

No quantitative counts of this species were made. It occurs over a fairly restricted depth range from 19 to 38 fathoms.

ROBERTINA CHARLOTTENSIS (Cushman)
Plate 102, figures 11, 12

Cassidulina charlottensis CUSHMAN, 1925, Contr. Cushman Lab. Foram. Res., vol. 1, pt. 2, p. 41, pl. 6, figs. 6, 7.
Robertina charlottensis (Cushman), CUSHMAN, 1933, Cushman Lab. Foram. Res., Spec. Publ. 5, pl. 27, figs. 9a, b.

Living specimens of this species occur from 20 to 150 fathoms in the Todos Santos Bay area, and its frequency distribution shows a distinct maximum between 30 and 40 fathoms. Both living and dead specimens are rare in the area studied.

ROBULUS sp.
Plate 101, figure 6

This species only occurred rarely in the samples studied and not abundantly enough to warrant exact identification. No living specimens were found, and the dead specimens occur in the area of relict sediments or near outcrops of Pliocene strata. This species may be reworked from "fossil" faunas.

"ROTALIA" cf. "R." BECCARII (Linné)
Plate 103, figures 12, 13

Nautilus beccarii LINNÉ, 1758, Syst. Nat., ed. 10, p. 710, pl. 19, figs. 1a–c.

Variants of this species occur in shallow water all along the coast of New England and Venezuela, in the Gulf of Mexico, and in the San Francisco Bay and a shallow brackish lagoon south of Seal Beach, California.

Living specimens in the Todos Santos Bay area occur only in one station from the Estero de Punta Banda. Dead specimens are common in both the marsh and channel subfacies of the estero.

ROTALIA spp.
Plate 103, figures 18, 19, 24

?*Rotalia versiformis* BANDY, 1953, Jour. Paleontology, vol. 27, p. 179, pl. 22, figs. 5a–c.

This form was originally described from off San Diego, California, and it occurs in great abundance between 100 and 200 ft. *R. lomaensis* Bandy, described from the same suite of samples, was not differentiated and may be included in the author's count.

Living specimens of these species do not occur deeper than 50 fathoms in the Todos Santos Bay area, and their frequency distribution shows a maximum between 10 and 20 fathoms. Dead specimens of these species are very common in Todos Santos Bay and occur to depths of 230 fathoms. Dead specimens are generally more abundant in the areas of relict sediments.

RUDIGAUDRYINA INEPTA
Cushman & McCulloch
Plate 100, figure 6

Rudigaudryina inepta CUSHMAN & MCCULLOCH, 1939, Allan Hancock Pacific Exped., vol. 6, no. 1, p. 94, pl. 9, figs. 3–10.

No living specimens of this species were found in the area studied. Dead specimens

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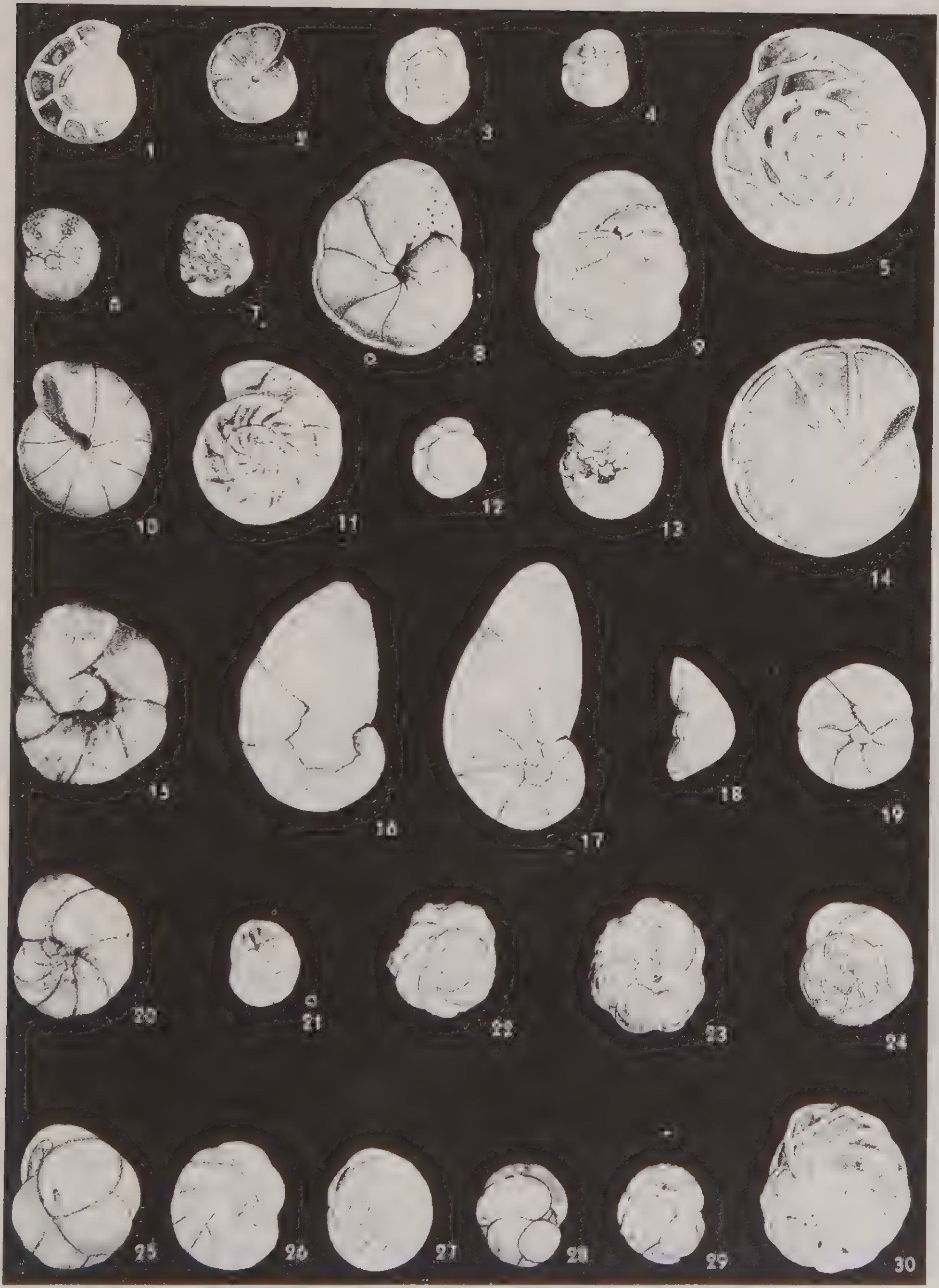
EXPLANATION OF PLATE 103

FIGS. *1, 2*—*Eponides subtenera* (Galloway & Wissler). ×46.
3, 4—*Bucella frigida* (Cushman). ×70.
5, 14—*Höglundina elegans* (d'Orbigny). ×46.
6, 7—*Discorinopsis* cf. *D. aguayoi* (Bermudez). ×46.
8, 9—*Eponides* cf. *E. repandus* (Fichtel & Moll). ×21.
10, 11—*Gyroidina altiformis* Stewart & Stewart. ×46.
12, 13—"*Rotalia*" cf. "*R.*" *beccarii* (Linné). ×46.
15, 20—*Valvulineria araucana* (d'Orbigny). (15) ×46; (20) ×33.
16, 17—*Valvulineria inaequalis* (d'Orbigny). ×33.
18, 19, 24—*Rotalia* spp. ×46
21—*Cassidulina subglobosa* H. B. Brady. ×46.
22, 23—*Epistominella smithi* (Stewart & Stewart). ×46.
25—*Cassidulina californica* Cushman & Hughes. ×33.
26, 27—*Cassidulina tortuosa* Cushman & Hughes. ×46.
28, 29—*Cassidulina delicata* Cushman. ×70.
30—*Cassidulina limbata* Cushman & Hughes. ×46.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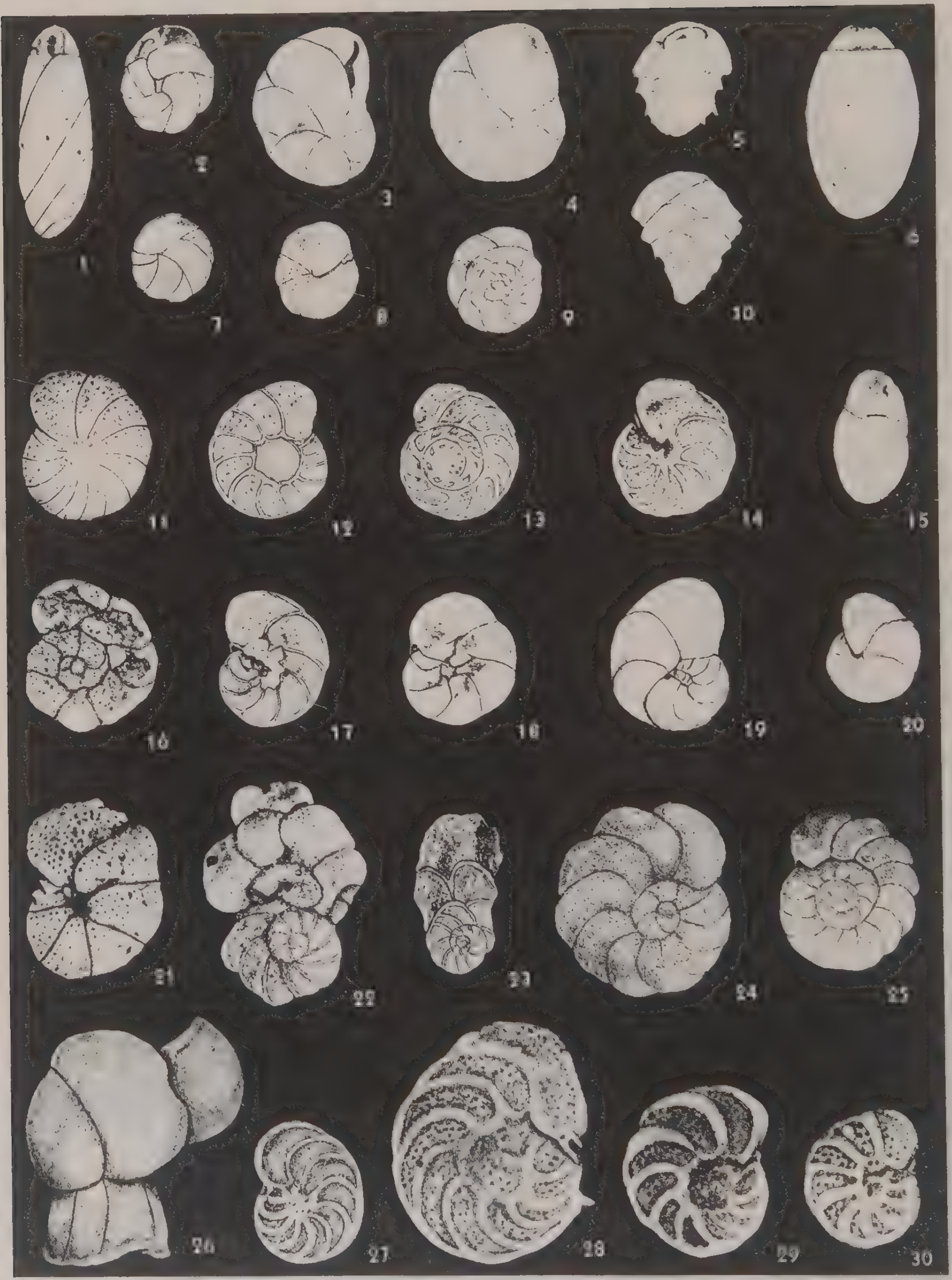
Walton, Living Foraminifera from Baja California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Walton, Living Foraminifera from Baja California

were found at only one station, in 39 fathoms.

RUPERTIA cf. R. STABILIS Wallich
Plate 104, figure 26

Rupertia stabilis WALLICH, 1877, Ann. Mag. Nat. Hist., ser. 4, vol. 19, p. 301, pl. 20.

No living specimens of this species were found in the area of Todos Santos Bay. It occurred dead in only one surface sample at 215 fathoms.

SIGMOILINA cf. S. MIOCENICA Cushman
Plate 100, figures 22, 23

Sigmoïlina tenuis (Czjzek), CUSHMAN, 1929, Contr. Cushman Lab. Foram. Res., vol. 5, p. 81, pl. 12, figs. 12–14.
Sigmoïlina miocenica CUSHMAN, 1946, Contr. Cushman Lab. Foram. Res., vol. 22, p. 33, figs. 19a–22.

This species appears to be more closely related to *S. miocenica* than to *S. tenuis*, and it differs from *S. tenuis* in that it has a shorter neck, broader test, and thick quinqueloculine portion of the test.

No living specimens of this species were found in the area of Todos Santos Bay. It occurs dead in the area of relict and fossil sediments and may indicate reworking of Pliocene strata.

TEXTULARIA cf. T. SCHENCKI
Cushman & Valentine
Plate 100, figures 7, 8

Textularia schencki CUSHMAN & VALENTINE, 1930, Contr. Dept. Geol., Stanford Univ., vol. 1, no. 1, p. 8, pl. 1, figs. 3a,b.

Living specimens of this species occur in the Todos Santos Bay area from 10 to 100 fathoms. It is generally most abundant between 30 and 40 fathoms. Dead specimens are common over most of Todos Santos Bay and occur down to depths of 215 fathoms.

TEXTULARIA cf. T. EARLANDI Parker
Plate 100, figure 5

Textularia elegans LACROIX, 1932, [not *Plecanium elegans* Mantken], Bull. Inst. Ocean. Monaco. 591, p. 8, text figs. 4, 6.
Textularia tenuissima EARLAND, 1933, [not Hausler, 1881], *Discovery* Repts., vol. 7, p. 95, pl. 3, figs. 21–30.
Textularia earlandi PARKER, 1952, Bull. Mus. Comp. Zool., vol. 106, no. 10, p. 458 [footnote].

Living specimens of this species occur between 10 and 30 fathoms. Both living and dead specimens occur rarely in the samples from Todos Santos Bay but dead specimens are fairly common in the channel stations of the Estero de Punta Banda.

TRILOCULINA sp. 1
Plate 100, figures 16–18

This species is small, well rounded, and almost transparent, and it has a single well-developed tooth. It is common in the Todos Santos Bay samples and only occurs shallower than 50 fathoms. It is most abundant between 40 and 50 fathoms. The distribution of the dead specimens generally corresponds with that of the living specimens.

EXPLANATION OF PLATE 104

FIGS. *1*—*Cassidulinoides* sp. ×46.
2, 7—*Cassidulina laevigata* d'Orbigny. ×70.
3, 4—*Cassidulina* sp. ×46.
5, 10—*Ehrenbergina compressa* Cushman. ×46.
6, 15—*Chilostomella ovoidea* Reuss. ×46.
8, 9—*Cibicides spiralis* Natland. ×46.
11, 12—*Cibicides fletcheri* Galloway & Wissler. ×46.
13, 14—*Cibicides mckannai* Galloway & Wissler. ×46.
16, 21—*Cibicides gallowayi* Cushman & Valentine. (16) ×33; (21) ×46.
17–19—*Cibicidina nitidula* Bandy. ×33.
20—*Pullenia salisburyi* Stewart & Stewart. ×46.
22, 23—*Dyocibicides biserialis* Cushman & Valentine. ×33.
24, 25, 29, 30—*Planulina exorna* Phleger & Parker. (24, 25) ×33; (29, 30) ×46.
26—*Rupertia* cf. *R. stabilis* Wallich. ×33.
27, 28—*Planulina* cf. *P. ariminensis* d'Orbigny. (27) ×21; (28) ×46.

TRILOCULINA sp. 2
Plate 100, figures 15, 21

This species is rather flattened and elongate, and it is characterized by a very prominent single tooth. Living specimens are restricted to the marsh subfacies of the Estero de Punta Banda, but dead specimens occur in the channel subfacies as well.

TRILOCULINA sp. 3

This species was only found at one station in the Estero de Punta Banda. Both living and dead specimens were present.

TROCHAMMINA INFLATA (Montagu)
Plate 100, figures 27–29

Nautilus inflatus MONTAGU, 1808, Test. Brit. Supp., p. 81, pl. 18, fig. 3.

This species is one of the most common forms in the marsh subfacies of the Estero de Punta Banda. Living specimens are restricted to the marsh subfacies, but dead specimens are common in the channel stations. No specimens were found outside the Estero de Punta Banda.

TROCHAMMINA KELLETTAE Thalmann
Plate 100, figures 25, 26

Trochammina peruviana CUSHMAN & KELLET, 1929, Proc. U. S. Nat. Mus., vol. 75, art. 25, p. 4, pl. 1, figs. 8a,b.
Trochammina kellettae THALMANN, 1932, Eclog. Geol. Helv., vol. 25, no. 2, p. 313.

Living specimens of this species are restricted to depths shallower than 30 fathoms in Todos Santos Bay. It generally occurs in small percentages, and its frequency distribution shows no marked maximum. Dead specimens are common over most of Todos Santos Bay and occur to depths of 490 fathoms.

TROCHAMMINA PACIFICA Cushman
Plate 100, figures 30, 31

Trochammina pacifica CUSHMAN, 1925, Contr. Cushman Lab. Foram. Res., vol. 1, pt. 2, p. 39, pl. 6, figs. 3a–c.

Living specimens of this species occur at most depths shallower than 200 fathoms. It is one of the most widely distributed species in Todos Santos Bay and is most abundant shallower than 30 fathoms. Dead specimens are very common in the bay and occur generally over the same depth range as the living specimens.

UVIGERINA PEREGRINA
Cushman variants
Plate 102, figures 22, 23

Uvigerina peregrina Cushman var. *curticosta* (Cushman), CUSHMAN & MCCULLOCH, 1948, Allan Hancock Pacific Exped., vol. 6, no. 5, p. 266, pl. 34, fig. 2.
Uvigerina peregrina Cushman var. *disrupta* TODD, in CUSHMAN & MCCULLOCH, 1948, Allan Hancock Pacific Exped., vol. 6, no. 5, p. 267, p. 34, fig. 3.

Living specimens of these species occur from 20 to 600 fathoms in the Todos Santos Bay area. Although the varieties were not differentiated, it is obvious from their frequency distribution (fig. 22) that each has a fairly discrete depth range. *U. peregrina* var. *disrupta* is the deeper, occurring with its maximum frequency between 250 and 300 fathoms. *U. peregrina* var. *curticosta* apparently occurs shoaler with its frequency maximum between 50 and 100 fathoms. Dead specimens of these species occur over approximately the same depth range as the living specimens.

UVIGERINA SENTICOSA Cushman
Plate 102, figure 24

Uvigerina senticosa CUSHMAN, 1927, Bull. Scripps Inst. Oceanog., Tech. Ser., vol. 1, no. 10, p. 159, pl. 3, fig. 14.

No living specimens of this species were found in the area of Todos Santos Bay. Dead specimens occurred at some of the deeper stations in the vicinity of outcropping Pliocene sediments. It is believed that this species may not represent a living population.

VALVULINERIA ARAUCANA (d'Orbigny)
Plate 103, figures 15, 20

Rosalina araucana D'ORBIGNY, 1839, Voy. Amer. Merid., Foraminiferes, vol. 5, pt. 5, p. 44, pl. 6, figs. 16–18.
Valvulineria araucana (d'Orbigny), CUSHMAN, 1927, Bull. Scripps Inst. Oceanog., Tech. ser., vol. 1, no. 10, p. 160, pl. 4, figs. 7, 8.

Living specimens of this species occur over a depth range of 150 and 600 fathoms in Todos Santos Bay, and the frequency distribution (Text-fig. 22) shows a maximum between 200 and 250 fathoms. The distribution of dead specimens corresponds generally with that of the living specimens.

VALVULINERIA INAEQUALIS (d'Orbigny)
Plate 103, figures 16, 17

Valvulina inaequalis d'Orbigny, 1839, Voy. Amer. Merid., Foraminiferes, vol. 5, pt. 5, p. 48, pl. 7, figs. 10–12.

Valvulineria inaequalis (d'Orbigny), Cushman, 1927, Bull. Scripps Inst. Oceanog., Tech. ser., vol. 1, no. 10, p. 161, pl. 4, figs. 9, 10.

Living specimens of this species occur deeper than 200 fathoms in Todos Santos Bay. It is rare in the samples studied and its frequency distribution shows no marked maximum.

VIRGULINA BRAMLETTI
Galloway & Morrey
Plate 102, figure 18

Virgulina bramletti Galloway & Morrey, 1929, Bull. Amer. Paleontology, vol. 15, no. 55, p. 37, pl. 5, fig. 14.

Living specimens of this species occur from 100 to 600 fathoms in Todos Santos Bay, and it is most abundant between 300 and 400 fathoms. The distribution of the dead specimens corresponds generally with that of the living specimens.

VIRGULINA SEMINUDA Natland
Plate 102, figure 19

Virgulina seminuda Natland, 1938, Bull. Scripps Inst. Oceanog., Tech. ser., vol. 4, p. 145, pl. 5, fig. 12.

Living specimens of this species occur from 100 to 400 fathoms in the Todos Santos Bay area and are generally rare in the samples studied. The distribution of the dead specimens generally corresponds with that of the living specimens.

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[From Proceedings of the JAPAN ACADEMY, Vol. 31 (1955), No. 10]

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152. *Bathymetry and Petrography of the Bayonnaise Rocks, Japan*[*)]

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(Comm. by S. TSUBOI, M.J.A., Nov. 12, 1955)

Introduction

Bayonnaise Rocks, lying at 31° 55.3′ N, 139° 54.5′ E, has been considered a portion of the somma of a submarine caldera volcano (Mita, 1946). Bottom configuration near the rocks was investigated by the Hydrographic Office of the Japanese Government and previous information regarding the rocks is summarized in the papers on the recent submarine eruption of Myojin Reef, formed near Bayonnaise Rocks in 1952 (Niino et al., 1953; Morimoto et al., 1955). So far as the authors know, prior to the present investigation no rock samples have been collected there. The University of California research vessel *Spencer F. Baird* visited the rocks in October, 1953, while on the Trans-Pacific Expedition, in order to collect such samples and to conduct a nearshore bathymetric reconnaissance.

Shortly after dawn on October 5 Warren S. Wooster, Trans-Pacific Expedition leader, Robert L. Fisher, geologist, and Stanley J. O'Neil, seaman, went ashore by skiff. Wind was from the east at 6 knots, swell 2–3 feet from the east, and surge on the rocks 3–4 feet. Submerged rocks were visible when the skiff was within 50 yards of the northern rocks, and waves were breaking 100 yards west of the westernmost exposed rock.

A landing from the northeast was made readily and 20–30 chips and hand specimens were collected. The stacks were rounded by wave erosion, with few ledges and no joint pattern apparent (Fig. 1). The rocks weather brown; the surface is further darkened by algal growth.

Meanwhile, the *Spencer F. Baird* made a single sounding traverse

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[*)] Contribution from the Scripps Institution of Oceanography, New Series, No. 815. This work represents one of the results of research carried out for the Office of Naval Research and Bureau of Ships, U. S. Navy, under contracts with the University of California.

around the rocks and then picked up the shore party. After another sounding circuit slightly farther from the rocks, the ship headed for Myojin-sho, passing about one mile south, and then one mile east, of its charted position (Fig. 2, inset). No projecting rock or evidences of eruption were visible but the presence of a bank at slight depth was indicated by a patch of whitecaps and pale green water.

Bathymetry

The results of the *Spencer F. Baird* bathymetric exploration of Bayonnaise Rocks are shown in Fig. 2. Soundings taken with a continuously-recording echo-sounder, operated on shoal scale, were plotted along the ship's track at one-minute intervals. Positions were taken at two-minute intervals, with visual bearings and radar ranges to the highest stack (Fig. 1, left) of the group. Soundings were taken in fathoms, employing an assumed sound velocity of 4800 feet (1463 meters) per second, and converted to meters.

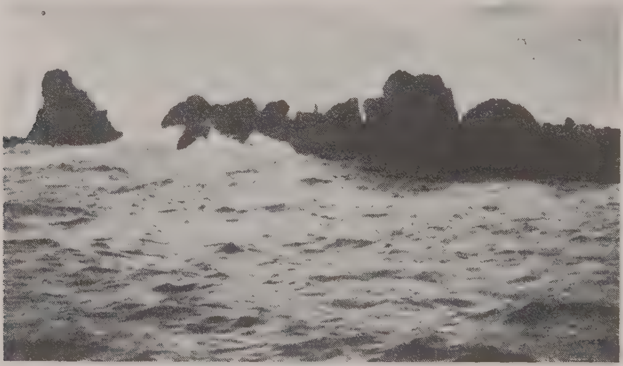

Fig. 1. Central portion of the Bayonnaise Rocks, from the northeast The sampled stack is shown in the right foreground.

In general, the present chart agrees rather well with previous plots of Bayonnaise Rocks (Niino et al., 1953, p. 43). The 1000-meter deep between Bayonnaise Rocks and Myojin-sho may well be a crater. Northwest-southeast elongation of the 100- and 200-meter contour lines is not well developed, although the 300-meter contour possibly should be extended southward. The nearly east-west trend of the exposed rocks cuts across the general trend of the contours, but is indicated by bulges of the 100-meter contour, as well as on the east side of the partly-drawn 50-meter contour. East of the rocks a valley or depression between two lobes can be traced from 50 meters down to at least 500 meters; it may debouch into the crater proper.

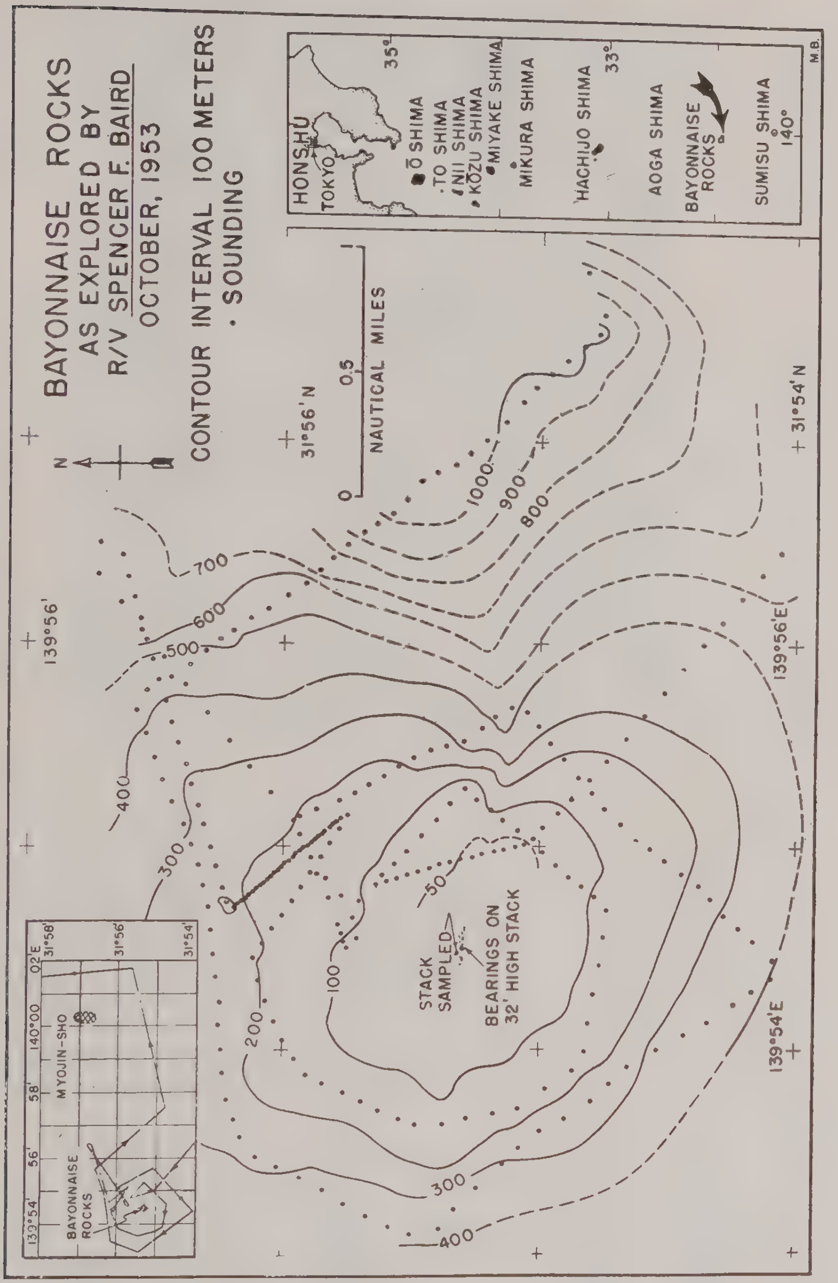
BAYONNAISE ROCKS
AS EXPLORED BY
R/V SPENCER F. BAIRD
OCTOBER, 1953
CONTOUR INTERVAL 100 METERS
· SOUNDING
N
0
0.5
NAUTICAL MILES
31°56'N
31°54'N
139°56'
139°56'E
139°54'E
50
100
200
300
400
500
600
700
800
900
1000
STACK SAMPLED
BEARINGS ON 32' HIGH STACK
HONSHU
TOKYO
35°
Ō SHIMA
TO SHIMA
NII SHIMA
KOZU SHIMA
MIYAKE SHIMA
MIKURA SHIMA
HACHIJO SHIMA
33°
AOGA SHIMA
BAYONNAISE ROCKS
SUMISU SHIMA
140°
M.B.
139°54'
56'
58'
140°00'
02'E
31°58'
31°56'
31°54'
MYOJIN-SHO
BAYONNAISE ROCKS

Fig. 2. Index maps and submarine topography near Bayonnaise Rocks

From the *Baird* soundings, Bayonnaise Rocks appears to be the summit of a nearly-equilateral peak lying on a northwest-southeast ridge. No good evidence of a shelf-break around the islands was found. Detailed sounding lines just north and south of the *Baird*-traversed area would make the depth contours drawn around Bayonnaise Rocks of comparable accuracy to those now drawn around Myojin-sho, based on the recent Japanese investigations.

Regional Relations and Petrography

The volcanic peak called Bayonnaise Rocks belongs to the Seven Izu-Ogasawara-Mariana island arc. All these islands are volcanic, the southward extension of the Fuji (Huzi) zone, along the petrographers' "andesite line" which here separates the Philippine Basin from the Pacific Basin proper. The Japan-Ogasawara-Mariana trenches parallel this arc on the east. The northward extension of this structure crosses Honshu at its central portion. Volcanism along the Seven Izu-Ogasawara-Mariana arc is considered to have begun in the Eocene and continued intermittently to the Recent; the present peaks are assumed to be of Quaternary origin (Tsuya, 1937).

Thus, the Bayonnaise Rocks—Myojin-sho volcano is very probably of Quaternary age, and possibly Recent. This age estimate is based on the apparently youthful shallow topography, i.e. lack of shelf-break, and the recently reported activity of Myojin-sho.

Petrographically, all the rocks collected from Bayonnaise Rocks are hypersthene-augite-anorthite basalt containing abundant anorthite phenocrysts (An_{91-99}), resulting in the relatively high CaO and comparatively low SiO_2 values of the chemical analysis. Porphyritic hypersthene ($En_{59}Fs_{41}$) and augite ($Wo_{40}En_{38}Fs_{22}$-$Wo_{45}En_{35}Fs_{20}$) are surrounded by pigeonitic augite of the groundmass. The groundmass consists of pigeonitic augite, pigeonite ($Wo_{12}En_{47}Fs_{41}$), bytownite (An_{75}), iron ores (magnetite), silica minerals (cristobalite, tridymite), and interstitial colorless glass (Fig. 3).

Chemical analysis indicates a high FeO:MgO ratio, high CaO, low alkalies, and saturation with silica. Results of analysis of a typical specimen follow:

SiO_2	51.95 Wt percent	$H_2O(+)$	0.21 Wt percent
Al_2O_3	18.85	$H_2O(-)$	0.18
Fe_2O_3	4.21	TiO_2	0.86
FeO	6.72	P_2O_5	0.07
MgO	3.96	MnO	0.18
CaO	10.85	NaCl	0.05
Na_2O	1.89	Total	100.22
K_2O	0.24		

(Anal. Joyo Ossaka, Earthquake Research Institute)

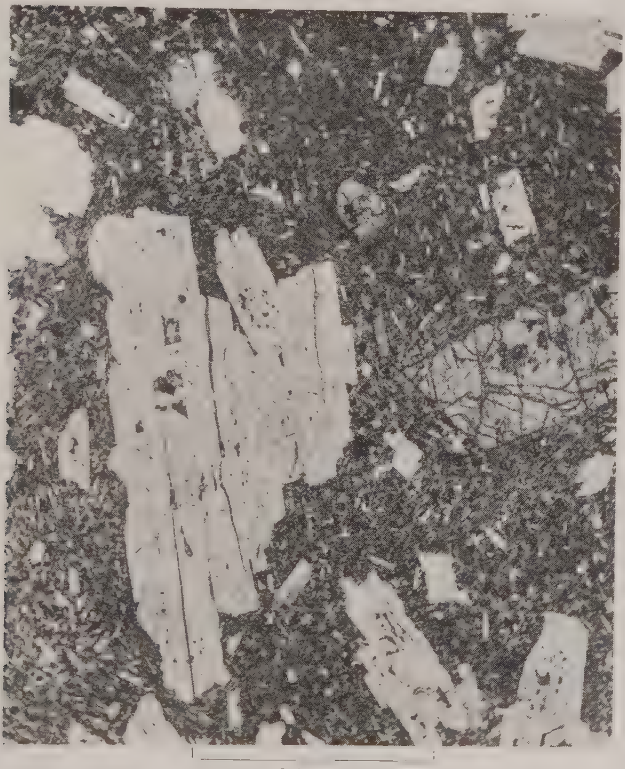

Fig. 3. Thin-section photomicrograph of a Bayonnaise Rocks specimen
White phenocrysts: Calcic plagioclase
Smaller gray phenocrysts: Hypersthene and augite
Groundmass: Pigeonitic augite, bytownite, magnetite, glass

Acknowledgments

The writers wish to thank Warren S. Wooster, scientific leader of the S. I. O. Trans-Pacific Expedition, and the officers and crew of the R/V *Spencer F. Baird* who assisted in the field study. They are grateful to Dr. Seitarô Tsuboi of the University of Tokyo for the interest in the project he has expressed.

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OIKOS 6:II 1955

AGGREGATION BY THE MARINE WOOD-BORING ISOPOD, *LIMNORIA*[1]

BY

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(Lamont Geological Observatory and U.S. Fish and Wildlife Service)

The infestation of wood by *Limnoria*, the marine wood-boring isopod, is initiated by swimming adult organisms. The available evidence, consisting of observations on animals in culture dishes, indicates that the finding of wood by the swimming animals is a matter of chance. The selection of wood as a burrow site is probably due to instinctive reactions of the organisms which are perhaps basically chemotropic in nature. Once wood is found the organisms appear to collect in clumps or aggregations.

To express the tendency of migrating adults to aggregate, wooden test blocks, which had been exposed in the sea at varying intervals of time, were divided into inch squares. The resulting number of burrows per square, from the forty squares on the upper and on the lower surfaces of each of fifteen blocks, was tabulated and tested for randomness (Table 1). If the burrows were distributed at random over the face of a block, the frequency distribution of number of burrows per square would be Binomial (BARTLETT, 1947). The mean of such a distribution would be forty times the probability that a single square contains a burrow. When this probability is low, the frequency distribution would approach that of a Poisson distribution. The variance (mean square deviation of a square's count from the mean count) of the binomial distribution is equal to the mean, times the complement of the probability that a square contains a burrow. The variance of the Poisson distribution is simply equal to the mean.

If the burrows are aggregated—contagious in their distribution—the variance of the frequency distribution of burrows will be greater than the mean count per square.

Even if the variance of the frequency distribution of burrows were not greater

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[1]) Contribution from the Scripps Institution of Oceanography, New Series, 816. These studies were aided by a contract between the Office of Naval Research, Department of the Navy, and the University of California, S. I. O., Nr. 163–084. Published by permission of the Director, Fish and Wildlife Service, U.S. Department of the Interior.

OIKOS 6:II, Copenhagen 1955

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Table 1.

Analysis of the frequency distribution of burrows per square inch of *Limnoria tripunctata* (Menzies) on 40 square inches of wood surface for each of 15 block, exposed to migrant attack in San Diego Harbor. "A" blocks located at Point Loma, "B" blocks located near San Diego ferry slip in San Diego.

Duration of Exposure	Station	Upper Surface				Under Surface			
		Mean	Variance		Index of Clumping	Mean	Variance		Index of Clumping
1 month.....	B	.30	.42	1.4	–	3.45	23.54	6.8	1.7
1 month.....	B	.55	3.82	6.9	10.8	.63	.91	1.5	–
1 month.....	B	.18	.25	1.4	–	.48	.67	1.4	–
1 month.....	B	.50	.97	1.9	1.9	9.13	72.83	8.0	.8
1 month.....	B	.53	1.18	2.2	2.4	4.05	22.10	5.5	1.0
1 month.....	A	.18	.25	1.4	–	.45	1.59	3.5	5.6
1 month.....	A	1.43	5.40	3.8	2.0	2.38	10.24	4.3	1.3
2 months....	B	2.23	6.55	2.9	.7	2.48	8.15	3.3	1.0
2 months....	B	1.10	1.94	1.8	.7	3.03	19.52	6.4	1.8
2 months....	A	.43	.76	1.8	1.9	.73	1.79	2.5	2.0
2 months....	B	2.13	15.24	7.2	2.9	4.5	27.38	6.1	1.1
2 months....	A	1.13	4.32	3.8	2.4	7.5	33.18	4.4	.5
3 months....	A	1.80	8.47	4.7	2.1	7.4	25.53	3.5	.3
3 months....	B	4.85	16.90	3.5	.5	5.0	8.85	1.8	.1
4 months....	B	6.60	20.09	3.0	.3	12.1	74.0	6.1	.4

than its mean "in the long run", it could often be greater than the mean when small samples are considered. The allowable ratio of variance to the mean in these samples of 40 squares, if there were a random distribution of organisms, is approximately 1.5, with 95% confidence. Hence, if the variance (estimated) of the burrows per square is greater than 1.5 times their mean, then their distribution on the block was not random, with 95% confidence.

The ratio of estimated variance to mean for each of the 15 blocks counted, for tops and for bottoms, is given in Table 1, in columns 3 and 7. In no instance is the ratio less than 1.4, and all but five are greater than 1.5. These five were blocks whose burrow density was low; generally less than one-half per square.

In the remaining ten blocks, the burrows were clumped to varying degrees. As an index of the degree of clumping or association,

$$\text{"}\lambda^2\text{" in:} \qquad s^2 = \bar{x} + \lambda^2\bar{x}^2$$

was computed. This relation between mean and variance is that from a negative binomial frequency distribution; one that has been used to describe contagion in the distribution of other animals. The greater the association of the animals, the higher λ^2 will be.

In the data presented, there appears to be a tendency for λ^2 to go down as the mean goes up. If the animals associate at low burrow densities, the λ^2 index should be high, but if they do not associate at higher burrow densities, λ^2 should go down, even though the distributions are not random. If the association is accomplished by an animal's scouting and burrowing close to wherever it finds evidence of another burrow, λ^2 would go down as the density of burrows went up. This is the case in the observed data.

Because five of the lower burrow density block surfaces were not significantly clumped, the scouting area of a single animal must be less than the area of the test blocks. On the other hand, clumping was in evidence at burrow densities down to about $\frac{1}{2}$ burrow per square, so the scouting area is probably greater than two square inches. From an inspection of the blocks, a scouting area of around four to eight square inches is inferred.

Only the burrow entrances, not other evidences of burrowing, were counted. Evidence of a burrow consists of both the single entrance opening and the several "blow holes" leading away from it for several millimeters along the surface of the wood. With a burrow density of two or three per square, the block's surface becomes fairly well covered with evidence of other animals, and the distribution of burrows on the block approaches uniformity.

Aggregations by *Limnoria* would seem to have some notable advantages to the species. First migrating individuals are not fertilized. A copulation must precede the production of each brood. This occurs only after a burrow is produced which is long enough to permit occupancy by both sexes (MENZIES, 1954). Aggregations then facilitate mate selection and reproduction by new arrivals and by sexually maturing organisms produced in the area. Second aggregations facilitate the penetration of water into the wood, allowing the construction of deeper burrows. Deeper burrows provided better protection of the young from predators. A disadvantage of the aggregations might lie in the more rapid production of an overcrowded state in which the available food supply is less than the demand of the organisms.

Summary

The distribution of burrows on wood as infestation proceeds can be summarized as follows:

1. The first few animals that arrive on the wood burrow nearly at random, having generally not found evidence of other animals within their scouting radius.

2. As infestation proceeds, the migrants are more apt to find other burrows or burrow evidence, and the distribution of the infestation becomes markedly aggregated.

3. Finally, as more and more animals arrive in the vicinity, the area of the clumps of infestation gets larger, and soon the burrows become nearly uniformly placed across the surface of the block.

4. In the formation of aggregations, it appears that the upper limits of the scouting range of one organism is between four and eight square inches.

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(Received 15.9.1955).

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Resources From The Sea

Man's Marine Treasure Chest*

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Approximately 71 per cent, or more than 140,000,000 square miles, of the earth's surface is covered with water. The comparative difference between water and land is even more pronounced when profiles are examined, the average depth of the sea being about 12,000 feet as compared with a mean land elevation of 2,300 feet. The highest point on the earth, Mount Everest in the Himalayas which is slightly more than 29,000 feet high, would be covered with about a mile of water if immersed in the Philippine Trench (34,560 feet deep) or the recently discovered Challenger Deep off Samoa (35,530 feet deep). If all the irregularities on the earth's surface were smoothed out (mountains, hills, plateaus, etc., leveled into submarine deeps, trenches and canyons), the entire sphere would be covered by a layer of water more than a mile thick.

This great mass of water, 330,000,000 cubic miles or a quadrillion (10^{15}) acre-feet, makes up about 98.5 per cent of the earth's total water supply. This water mass has far-reaching effects on world weather, climate, communications, pathways of commerce, recreation and in the strategem of national defense. It contains a vast potential of natural resources including biological products, power and minerals.

With a mineral content of nearly 3.5 per cent, there is enough mineral matter to cover the world above sea level with a layer about 500 feet thick. Approximately 85 per cent of it consists of sodium chloride or common table salt, but sea water is also relatively rich in magnesium, calcium, potassium, sulfur (primarily as sulfate), bromine and iodine. Virtually all known elements occur in the sea.

Some of these minerals, notably sodium, chlorine, bromine, iodine, and magnesium, are now being extracted from the sea in commercial quantities. The extraction of common table salt from sea water is the oldest chemical industry. Such salt, once used to pay wages, gives us the word salary (from Latin **salarium**). Solar salterns at San Diego and San Francisco yield more than two million barrels of salt each year. The total exploitations of man, though, seem insignificant in view of the vast storehouse of salt in the sea; a storehouse which is being replenished at an annual rate of five trillion tons carried into the sea by the rivers of the world.

As technological processes are perfected and terrestrial supplies are depleted, man will be looking more and more toward the sea as a source of raw products. Commercially valuable minerals extracted as by-products will help to make practical the desalting of sea water for agricultural, industrial and culinary uses.

Water Desalted

At the present time engineers estimate that sea water can be desalted by the electric membrane method for about 30 cents per 1,000 gallons, but this estimate does not include cost of delivery or removal of spoil. Compressive distillation, multiple effect distillation or the freezing method currently cost more, but with perfection of procedures by research, advent of cheaper power, large-scale operations or profits from mineral by-products, the cost may be reduced to an economic level.

Another important mineral resource believed to be almost exclusively of marine origin is oil. It is the consensus of petroleum geologists that crude oil was formed in ancient shallow seas where the rate of organic production was high and sedimentation rapid. Accumulating evidence suggests that oil is currently being formed from the modification of marine organisms buried in certain sedimentary environments. Tidelands and the inshore continental shelf probably hold petroleum reserves exceeding all known deposits on land.

In the sea as on the land the greatest resource is organic productivity; the capacity to produce food. Both plants and animals abound in the sea. In fact, acre for acre the world over, the sea seems to be more productive of both plants and animals than the soil although man has yet to learn how to harvest much of the marine crop.

Since sea water is a physiologically balanced salt solution containing an abundance of nearly all the minerals essential for life, it is an excellent medium for the growth of aquatic plants and animals. Only fixed nitrogen and phosphate occasionally become limiting factors in certain areas, but these plant nutrients, along with several others, are continually being drained from the soil into the sea. There are unlimited supplies of nitrate and phosphate in the deep sea below the photosynthetic zone awaiting the ingenuity of man to devise practical ways to bring them back to the surface.

The depth at which plants grow in the sea is determined by the penetration of water by sunlight, a depth of a few hundred feet in many parts of the ocean. This may be contrasted with conditions in the world above sea level where plant production is confined to the topmost few inches of soil or a few feet at the most. Terrestrial animals, like plants, are largely confined to a relatively thin layer of soil, but in the sea, animals of many kinds have been found at about 35,000 feet, the greatest depths explored.

Favorable Temperatures

Temperatures in the marine biosphere are more favorable for the growth of organisms than in most parts of the world above sea level. A large percentage of the land mass is frozen during all or part of the year, particularly at high elevations or at high latitudes as above the Arctic and Antarctic Circles. In much of the Torrid Zone and in extensive areas within the Temperate Zones, the temperature is often too high for the optimum growth of plants. Contrast the extremes of terrestrial temperatures, minus 50° F to 150° F above, with conditions in the sea where from the Equator right up to the fringe of Polar icecaps, the water temperature ranges from about 30° F above to a maximum of 70 or 80° F.

Dr. Claude E. ZoBell, professor of microbiology at Scripps Institution of Oceanography, is shown adjusting a ZoBell water sampler used for collecting samples of sea water from any desired depth down to 200-meters (656.16-feet).

Unlike large land areas in our own Pacific Southwest, most of central and western Australia, the Sahara and Gobi Deserts, for example, where plant growth and animal survival are limited by lack of water, there is always plenty of life-giving water for an abundant growth of plants in the sea.

More than 6,000 species of marine plants have been described. The majority of these are small algae, diatoms and dinoflagellates, although there are hundreds of larger plants commonly called seaweeds.

Ocean Pasturage

Diatoms, dinoflagellates and other microscopic algae, collectively called phytoplankton, constitute the ocean pasturage, the principal food for marine animals. Just as the amount of grass or clover in a fertile field on which cattle or sheep are grazing and becoming fat may not be very great at any one time, so also the standing crop of phytoplankton ordinarily is not very great except in localized areas. As in the fertile field, though, the rate of growth of the phytoplankton may be rapid enough to support an extensive population of grazing animals. Many marine animals, ranging in size from tiny copepods to monstrous whales, are adapted to feed and fatten on phytoplankton filtered or strained from sea water.

Most phytoplankton are highly nutritious, being relatively rich in energy-yielding substances, proteins, vitamins, and essential minerals. A properly equipped person, ship-wrecked at sea or just experimenting with a different diet, might be able to subsist on phytoplankton, but a practical procedure for the large-scale harvesting of phytoplankton to feed famished populations has yet to be developed.

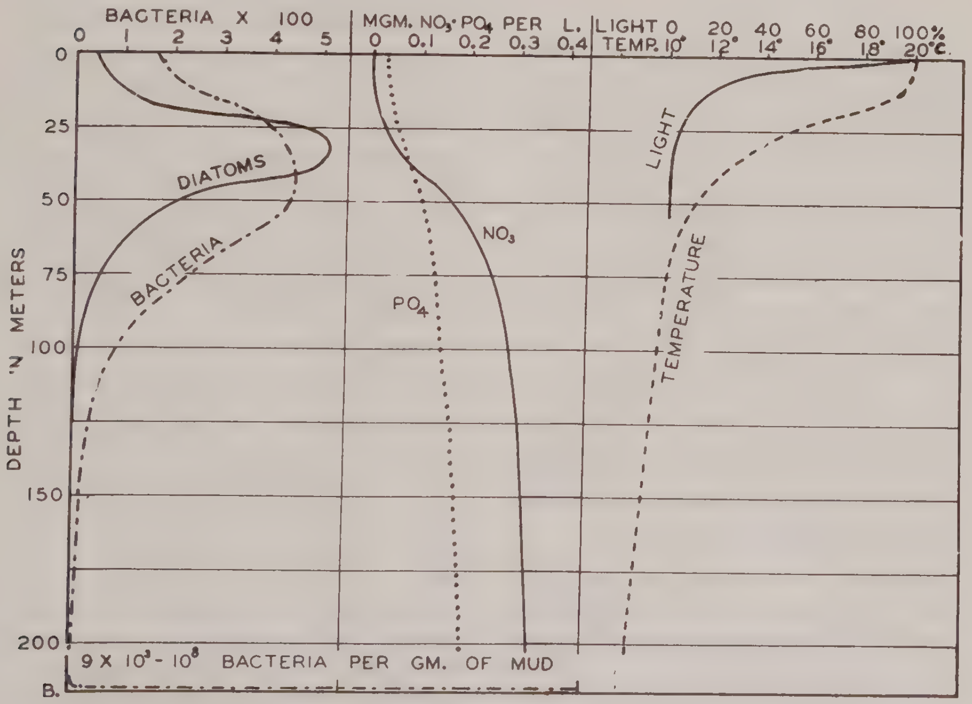
Edible seaweeds are much easier to harvest than the highly dispersed though more abundant phytoplankton crop. In America such seaweeds as agar-agar, dulse, Irish moss, and nori, are utilized primarily as food conditioners or adjuncts. In the Orient, however, and throughout Oceania, sea weeds are an important part of the diet.

Seaweed Harvest

Seaweeds are extensively harvested in different parts of the world for such purposes as fertilizers, mulching agents, stock feeds, pharmaceuticals, cosmetics, paper sizing and gelling agents. Thousands of tons of giant kelp and other seaweeds which used to rot in the sea or wash ashore are now harvested for the extraction of alginates. Alginates, sold under various trade names, are used as stabilizers of emulsions or suspending agents in ice creams, sherbets, chocolate milks, cream cheeses, bakery products, cosmetics, pharmaceuticals, paints, printing inks, paper coatings, sealing compounds, oilwell drilling muds, insecticides and scores of other products.

It is a great pity that more seaweeds are not harvested along our coast and used for the good of man because great amounts still wash ashore to litter our beaches. But this is still only a fraction of what used to wash ashore before any was harvested. The harvesting of kelp is a good example of the practical conservation of an important marine resource. The harvesters operating off our coast have improved the condition of the kelp beds by removing old growth and preventing its washing ashore. State law provides that kelp shall not be cut at a depth greater than four feet below the water surface. When so cut, new fronds quickly grow to take the place of those that were harvested, thus making it possible to harvest three or four crops per year.

Dollarwise and otherwise, animal products from the sea many times exceed the marine plant products. The commercial fishing industry of the U.S. and Alaska last year (1954) tallied a catch of more than three million tons of fish, the employment of more than half a million men and the use of 88,000 fishing boats. The annual fish



The composite chart above shows from left, the ocean's vertical distribution of plants (bacteria and diatoms); vertical distribution of plant nutrients (phosphate and nitrate), and the vertical penetration of sunlight and the temperature by depth of the sea. Comparatively little light penetrates the ocean to depths greater than 50-meters, 164.04-feet). The water temperature below this depth is also approximately 3° C. As shown in the chart on the left, bacteria are usually very abundant in bottom deposits at all depths.

catch in all countries which keep such statistics exceeds 20 million tons. Perhaps more than this amount of fish is caught and consumed without entering world commerce records.

Marine birds harvest tremendous tonnages of fish, but most of this is lost to man except for the end-product guano. Whether this is economic is highly controversial. Certainly from a viewpoint of conservation it is not very efficient for man to get his food from soil fertilized with guano from fish which have harvested marine plants. Eliminating these extravagant "middlemen" would materially increase the amount of food available for man if only he knew how to directly harvest and utilize the marine plants.

Shellfish

Harvested to the extent of millions of tons per year are oysters, clams, cockles, mussels and other shellfish. Unfortunately, oyster production in many parts of the world is on the decline owing to overfishing, disease and the disturbance of oyster beds by dredging, pollution, etc. Proper practices could increase oyster production tenfold in many beds. Moreover, there are a good many other shellfish yet to be exploited. Besides serving as nutritious food for man, poultry and hogs, shellfish provide calcareous shell products, mother of pearl and numerous other products of commerce.

Although taken and processed primarily for their oil content, whales, dolphins and porpoises provide many other products, including meat for human or animal consumption, baleen, ivory, ambergris, hides, pharmaceuticals, meat extracts, bone meal and a long list of chemical compounds. Catching and processing whales gives gainful employment to millions of men.

Books have been written outlining the tonnages, dollar value, food content, economic significance and occupational importance of marine fish, oysters, lobsters, whales, turtles, sponges, fur seals, seaweeds and other marine products. Suffice it to say here that the totals are stupendous and have a tremendous impact upon our civilization. Nevertheless, it is somewhat depressing to the oceanographer to be reminded that in spite of the preponderance of productive water over land area, the ocean provides less than 10 per cent of man's food. From this you will grasp the awful truth that even should the harvest from the sea be doubled, it would do relatively little to alleviate the world's food shortage. However, if the useful harvest from the sea could be made commensurate with its primary productivity, the outlook for the future would be different. Hoping for such a situation may seem an idle dream, and yet it may be no more fantastic than it would have been two or three centuries ago for the American Indian to have dreamed of food from the Great Plains region being increased several hundredfold.

There may be many ways to augment the harvest from the sea by improved harvesting and processing methods. We may find further uses for marine animals and particularly for marine plants. Aquiculture or the cultivation of useful aquatic plants and animals holds promise since fish farming and the fertilization of small arms of the ocean have proved to be practical. If controlling predators, parasites and unwanted animals competing for food and living room in the sea seems to be an impossibility, it is only because we know so little regarding conditions of life in the sea. We have only to look at the progress in agricultural pursuits, scientific range management or modern-day forestry practices to find encouraging analogies. Most agricultural products, fruits, cereals, root crops, domestic animals, are the result of generations or centuries of careful improvement of stocks and strains by selection and crossbreeding. Perhaps in a similar way the principles of genetics can be applied to the development of bigger, better, more nutritious, disease-resistant or otherwise more desirable marine plants and animals.

My only answer to the hundreds of objections voiced is to say that exploration, research and application of good engineering to the problem may show the way.

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*Contribution from the Scripps Institution of Oceanography, New Series, No. 817.